(2)

HSD-TR-87-013

AD-A200 125

A STRATEGY FOR UNDERSTANDING NOISE-INDUCED ANNOYANCE

S. Fidell
D.M. Green
T.J. Schultz
K.S. Pearsons

BBN Laboratories Incorporated
21120 Vanowen Street
Canoga Park, CA 91303

August 1988

Final Report for Period January 1987 - September 1987

Approved for public release, distribution is unlimited.

Noise and Sonic Boom Impact Technology Program
Human Systems Division
Air Force Systems Command
Brooks Air Force Base, TX 78235-5000

88 10 5 316

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility nor any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise as in any manner construed, as licensing the holder, or any other person or corporation; or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed and it is releasable to the National Technical Information Service (NTIS), where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Geral L. Long

GERAL L. LONG, LT COL, USAF
NSBIT Program Manager

FOR THE COMMANDER

Michael G. MacNaughton

MICHAEL G. MACNAUGHTON, COL, USAF
Deputy Commander Development & Acquisition

Please do not request copies of this report from the Human Systems Division. Copies may be obtained from DTIC. Address your request for additional copies to:

Defense Technical Information Center
Cameron Station
Alexandria VA 22301-6145

If your address has changed, if you wish to be removed from our mailing list, or if your organization no longer employs the addressee, please notify HSD/SORT, Brooks AFB TX 78235-5000, to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS: None

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): BBN Report No. 6337

5. MONITORING ORGANIZATION REPORT NUMBER(S): HSD-TR-87-013

6a. NAME OF PERFORMING ORGANIZATION: BBN Laboratories Incorporated

6b. OFFICE SYMBOL (If applicable): BBN

7a. NAME OF MONITORING ORGANIZATION: Noise and Sonic Boom Impact Technology (NSBIT) Program, Human Systems Division

6c. ADDRESS (City, State and ZIP Code): 21120 Vanowen Street, PO Box 633, Canoga Park, CA 91303

7b. ADDRESS (City, State and ZIP Code): HSD/YA - NSBIT, OL-AC WPAFB OH 45433-6573

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Noise and Sonic Boom Impact Technology Program

8b. OFFICE SYMBOL (If applicable): HSD/YA-NSBIT

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-86-C-0530

8c. ADDRESS (City, State and ZIP Code): HSD/YA-NSBIT, OL-AC WPAFB, OH 45433-6573

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
63723F	3037		

11. TITLE (Include Security Classification): A Strategy for Understanding Noise Induced Annoyance (Unclassified)

12. PERSONAL AUTHOR(S): S.Fidell, D.M.Green, T.J.Shultz & K.S.Pearsons

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 01/01/87 TO 09/29/87

14. DATE OF REPORT (Yr., Mo., Day): ~~1988 June 16~~ AUG 88

15. PAGE COUNT: 118

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB. GR.
05	08	
24	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Annoyance; Aircraft Noise; Community Response; Noise; Psycho-acoustics

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report provides a rationale for development of a systematic approach to understanding noise-induced annoyance. Two quantitative models are developed to explain 1) the prevalence of annoyance due to residential exposure to community noise sources; and 2) the intrusiveness of individual noise events. Both models deal explicitly with the probabilistic nature of annoyance, and assign clear roles to acoustic and nonacoustic determinants of annoyance. The former model provides a theoretical foundation for empirical dosage-effect relationships between noise exposure and community response, while the latter model differentiates between the direct and immediate annoyance of noise intrusions and response bias factors that influence the reporting of annoyance. The assumptions of both models are identified, and the nature of the experimentation necessary to test hypotheses derived from the models is described.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: LT COL GERAL LONG

22b. TELEPHONE NUMBER (Include Area Code): 513-255-8416

22c. OFFICE SYMBOL: HSD/YA-NSBIT

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

Table of Contents

List of Figures

Acknowledgments

The authors acknowledge the advice received from Air Force personnel in the course of preparing this report. Special appreciation is extended to Mr. Lawrence S. Finegold (NSBIT ADPO) for his suggestions concerning the conduct of this research and for his comments on the draft versions.

The authors also thank Dr. William Galloway for his helpful comments on drafts of this report, and an anonymous Air Force editor for stylistic changes.

Executive Summary

The National Environmental Policy Act of 1969 (NEPA) and other regulations require the U.S. Air Force (USAF) to predict noise-related effects of its flight operations. Predicting the annoyance associated with residential exposure to sonic booms and to low-altitude, high-speed flight is an essential part of the environmental assessment process for military operating areas (MOAs) and military training routes (MTRs). However, USAF environmental planners currently lack the tools to accurately predict the prevalence of noise-induced annoyance. The state of the art annoyance prediction also leaves the USAF's environmental impact estimates open to technical challenges.

This report develops a systematic approach to understanding noise-induced annoyance in the residential setting. Empirical verification of hypotheses derived from this view of annoyance is the first step in developing tools that environmental planners can use to systematically predict the intensity and extensity of aircraft noise-induced annoyance. Equally important, a theoretically based and empirically verified understanding of annoyance is expected to help to distinguish between two components of annoyance: direct annoyance, based on a listener's sensitivity to immediate characteristics of acoustic signals, and response bias, based on *nonacoustic factors*.

Chapter 1 points out that variability is such an essential characteristic of annoyance that deterministic models of annoyance have limited usefulness. The introductory discussion notes that acoustic variables alone do not always suffice to predict the prevalence of annoyance, and that acoustic variables therefore may not always be regarded as strictly causal. A critical distinction is then made between two components of self-reports of annoyance: an acoustically related component, and response bias.

Chapter 1 also reviews the state of the art of predicting community response associated with residential exposure to general transportation noise and high energy impulsive noise. This review leads to the conclusion that the USAF can not currently isolate the fraction of community response that is directly caused by noise exposure.

Annoyance is then differentiated from loudness and complaints: loudness is a sensation, complaining is a behavior, and annoyance is an attitude. A further distinction is made between primary and secondary annoyance; the former is associated more or less immediately with noise exposure, while the latter is mediated by other effects of noise (e.g., communication and activity interference) on people.

The following chapters of the report develop macro- and micro-scale models of annoyance.

Chapter 2 presents a model of the aggregate annoyance of multiple noise intrusions to populations of individuals. This model supplies a theoretical underpinning for empirical dosage effect relationships such as that developed by Schultz (1978) and CHABA Working Group 84 (1984). The first model is based on the assumption that different individuals in a community accumulate different noise burdens due to differences in time spent at home and due to the heterogeneity of exposure throughout a community. A given outdoor noise exposure is assumed to generate an exponential distribution of individual noise doses. It is then assumed that exposure must exceed a criterion level before it is reported to be highly annoying. This criterion may vary for any number of nonacoustic reasons, but is generally set high enough that it is rarely exceeded by a noise exposure associated with the distant portion of the neighborhood ambient noise distribution (see Appendix B and the Glossary for explanations and definitions of these terms).

Sample calculations based on these assumptions are then performed so that the theoretically predicted dosage-effect relationship may be compared with the empirical relationship derived by Schultz. The simple exponential model is shown to produce an excellent fit to Schultz's relationship. It can also provide a complete account of differences between Schultz's relationship and alternative relationships through the variation of a single parameter. This parameter, the criterion value for reporting annoyance, is a measure of response bias, not annoyance per se.

Chapter 3 presents additional background about the annoyance of individual noise intrusions prior to the development of a formal theoretical approach to development of a micro-scale model in Chapter 4. The initial discussion in this chapter concerns the conventional (deterministic and largely atheoretical) view of annoyance and its historical origins. A series of issues that should be examined by a complete theory of annoyance is presented next, followed by a closer examination of existing methods of accounting for annoyance phenomena. The chapter concludes with a presentation of evidence that supports a decision-theoretical approach to modeling the annoyance of individual noise intrusions.

Chapter 4 contrasts descriptive and prescriptive theories to clarify the basis for the current preference for a prescriptive approach. A detailed model is then developed. Annoyance is treated as a rational process in which people act as though they decide whether a particular noise intrusion is either nonannoying or annoying with respect to a criterion. Annoyance judgments are regarded as the product of this discrimination, so that the likelihood of an annoyance judgment increases as the integrated detectability of the noise intrusion grows with respect to a reference noise distribution.

Considerable detail is provided about the nature of the reference distribution, the optimal strategy for fixing the criterion level for reporting annoyance, and the roles of conventional Bayesian variables and two classes of nonacoustic variables: affective state, and concentration

on ongoing activity. Assumptions necessary to derive quantitative predictions from the model are stated, and working assumptions are made to permit spreadsheet calculations of model predictions.

The questions raised earlier in the report about issues that a theory of annoyance should examine are then reconsidered in the context of the model. Chapter 4 concludes with a discussion of some limitations of the model.

Chapter 5 describes the research necessary to provide empirical tests of hypotheses derived from the theoretical model. The report concludes with several major appendices that should assist readers without extensive backgrounds in environmental acoustics and decision theory to understand the concepts developed in the body of the report.

Foreword

This report was prepared under Contract F33615-86-C-0530 of the Noise and Sonic Boom Impact Technology (NSBIT) Program. The NSBIT program is conducted by the United States Air Force Systems Command, Human Systems Division, under the direction of Lt. Col. Geral Long, Program Manager.

The work described in this document represents the initial step of an intended series of annoyance-related research and development efforts sponsored under this program. Other studies of the NSBIT program are directed towards improving methods for predicting the generation, propagation, and effects of subsonic and supersonic aircraft noise on human health, as well as on physical structures and wild and domestic animals.

1. INTRODUCTION

This report develops a rationale for approaching the study of noise-induced annoyance as required by the Task 0004 Work Statement of Contract F33615-86-C-0530. Subsequent efforts, briefly outlined in the latter part of this report, are expected to lead to the development of practical tools that the USAF environmental planning community can use to prepare and defend the environmental assessments required under the National Environmental Policy Act (NEPA) and other regulations.

1.1 Noise-Induced Annoyance and the Environmental Assessment Process

One of the most widespread effects that individuals and residential populations associate with aircraft noise exposure is annoyance. In fact, annoyance is the implicit basis for noise-related habitability criteria, such as those adopted by various government agencies including the Department of Defense (Galloway, 1974; CHABA, 1979; ANSI, 1980). Under some conditions, annoyance can also become the most serious and long-lasting basis for political and legal challenges to USAF flight operations. Prediction of the intensity and extensity of residential annoyance associated with flight operations is therefore a central issue that must be examined by USAF planners in preparing environmental assessments.

Two fundamental problems confront all who attempts to predict the annoyance produced by aircraft noise exposure. The first is that considerable variability has been observed in the prevalence of annoyance both within individuals and from community to community for the same exposure conditions. Variability is so characteristic of annoyance that serious efforts to understand the problem must confront this variability issue squarely.

Since acoustic variables alone usually do not fully predict the intensity and extensity of annoyance, there is a clear need to provide a systematic account of the influence of nonacoustic factors on annoyance judgments. Attributing all failures to predict annoyance to "individual differences" accomplishes little, since individual differences also have causes that require systematic understanding.

Given that nonacoustic factors indisputably affect the asserted annoyance of aircraft noise, the second fundamental problem is distinguishing direct annoyance (that directly attributable to exposure) from response bias (the willingness to report annoyance independently from its acoustic determinants) in a nonarbitrary manner. This discrimination is a critical task, because of the need to demonstrate that noise is not always the only cause of annoyance.

A "cause" is a necessary and sufficient antecedent condition. Although noise exposure is often necessary to provoke annoyance, it is not always sufficient, and therefore it cannot always be regarded as strictly causal. It is in this sense that the USAF cannot logically be held responsible for causing reports of annoyance that are engendered by nonacoustic factors.

1.2 Current Practice in Annoyance Prediction

The basic tool now available to environmental planners to predict the prevalence of noise-induced annoyance is a dosage-effect relationship synthesized by Schultz (1978), and reproduced here as Figure 1-1. This empirical relationship was developed from the data of social surveys conducted world-wide on the annoyance of general transportation noise, as described in Appendix A. Schultz's relationship permits nominal estimation of the proportion of a residential population that is likely to be highly annoyed in terms of an integrated measure of noise exposure, the Day-Night Average Sound Level (abbreviated as DNL and written symbolically as L_{dn}). Even though Schultz's relationship provides the most thoroughly documented and authoritative guidance available, environmental planners cannot rely on it exclusively to prepare or defend the annoyance-related portion of environmental assessments for the following reasons:

1) Schultz's relationship is based only on general transportation noise, including conventional subsonic aircraft noise. It is not intended to predict the annoyance associated with exposure to impulsive (supersonic) flight noise, nor to low altitude, high speed flight noise. A separate relationship (developed by CHABA Working Group 84 [Galloway, 1984] and reproduced here as Figure 1-2) dealing with annoyance due to impulse noise is not as well established as that of Schultz.

2) Schultz's relationship is a purely empirical, synthesized by averaging data from a score of studies relating noise exposure to community response. Lacking a theoretical foundation, its application to any particular situation is frequently challenged on the grounds of special circumstances, such as demographic or historical factors peculiar to a local setting.

3) In the absence of systematic understanding of noise-induced annoyance, interpretations of empirical data other than those developed by Schultz may be cited in opposition to an environmental assessment based on Schultz's dosage-effect relationship.

In short, even proper use of the best information does not guarantee that annoyance predictions associated with USAF operations can withstand the scrutiny of an adversarial environmental assessment process. The realities of the environmental assessment process encourage those who contesting findings on technical grounds, even for interests which are not

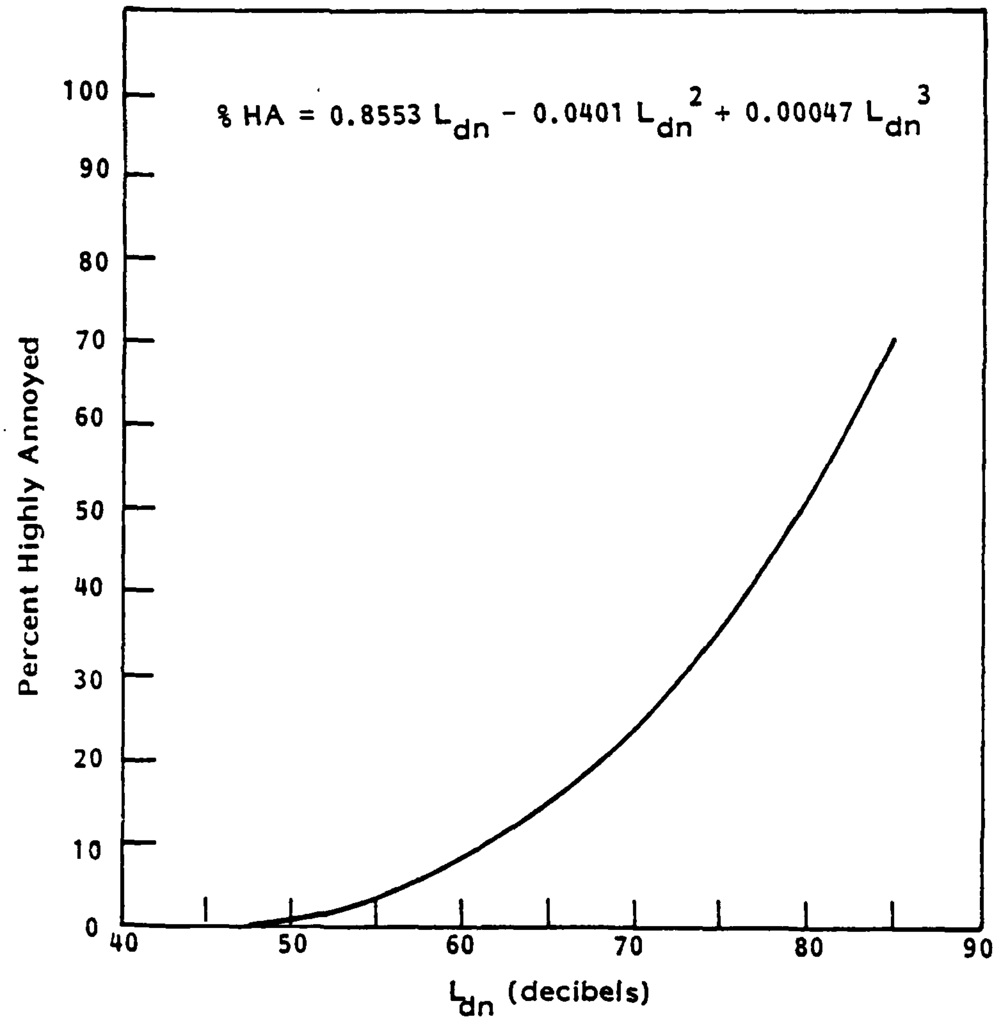

Figure 1-1: Dosage-Effect Relationship for Predicting the Prevalence of Annoyance Associated with General Transportation Noise Exposure (Schultz, 1978)

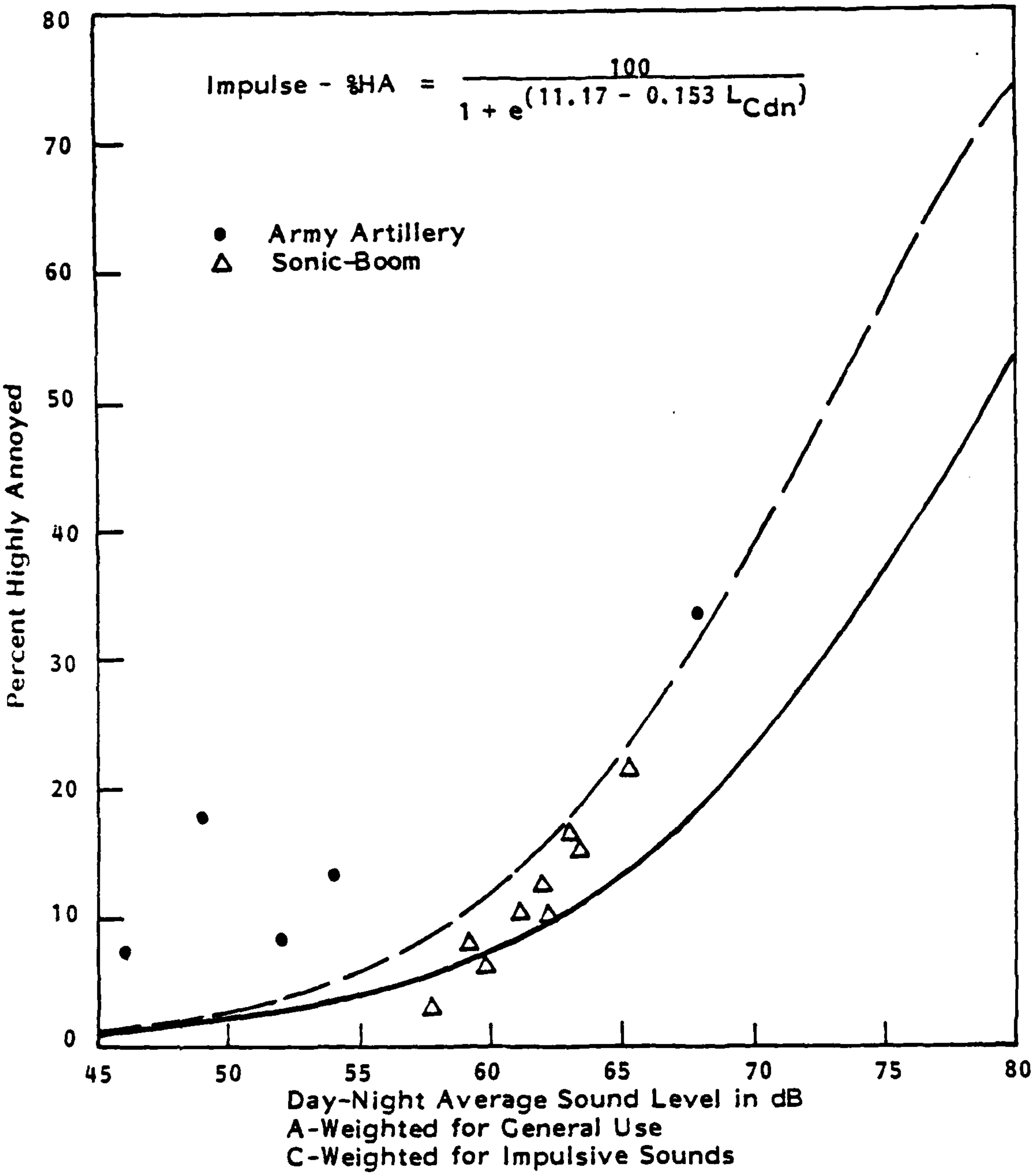

Figure 1-2: CHABA Working Group 84 Relationships for Predicting Community Response to High Energy Impulsive Sounds and to Other Sounds

exclusively acoustic. For example, it is not uncommon for economic and other concerns to find expression in annoyance-related terms. Right or wrong, the adequacy of predictions of noise-induced annoyance therefore plays major roles in challenges to USAF environmental assessments.

Without a quantitative understanding of the contribution of nonacoustic factors to noise-induced annoyance, however, the Air Force cannot persuasively identify the fraction of community response that is directly caused by noise exposure. A major goal of the research described in this report is to develop a systematic and defensible rationale for distinguishing between annoyance caused by acoustic *vs.* nonacoustic.

1.3 Difficulties in Defining Annoyance

Noise-induced annoyance is a chameleon-like concept that eludes succinct definition. Annoyance differs from loudness in at least two obvious respects.

First, annoyance increases with exposure duration, whereas loudness does not increase with duration beyond about a quarter of a second (Zwislocki, 1969). Second, loudness is a nearly immediate sensation with no appreciable cognitive component.

Annoyance is neither a sensation nor a physical quantity, but rather an attitude, a covert mental process with emotional and cognitive components. It is usually thought of as a generalized adverse attitude toward noise exposure, although this is hardly a definition specific enough to be useful for many purposes. In the environmental planning context, "community response" is often used as a synonym for annoyance.

It is important at this point to distinguish annoyance from complaints. Annoyance is an attitude, while complaining is a behavior. When complaints are assumed to be motivated by annoyance, they are often regarded as tangible manifestations of annoyance (e.g., so many telephone calls to a hotline, so many letters, so much litigation). There is no necessary or direct linkage between annoyance and complaints, however. It is not unusual for complaints to be made in the absence of noise exposure, in anticipation of future noise exposure, or after the cessation of noise exposure. Many more factors intervene between noise exposure and complaints than between noise exposure and annoyance. These include expectations about the outcomes of complaining, and the knowledge and resources necessary to continue complaint behavior. The research described in this report is directed at understanding annoyance, not complaints.

It is also important to distinguish annoyance from other behavioral consequences of noise

exposure, such as the actions summarized in Figure 1-3, because annoyance can arise from noise exposure that produces no behavioral effects at all. People may report annoyance in the absence of hearing damage, startle, speech interference, sleep interference, or any other overt response to noise.

On the other hand, annoyance can sometimes be an indirect, second-order effect of other effects of noise on people. Annoyance frequently accompanies interference with communication, ongoing behavior, and sleep; it can accompany hearing damage or startle; and it can even be thought of as either a cause or an effect of physiological stress. Figure 1-4 illustrates schematically some of the linkages between noise exposure and annoyance. Although Figure 1-4 emphasizes associations between annoyance and other effects of noise on people, it falls short of expressing the total number and nature of the relationships that must be understood before annoyance can be predicted from noise exposure and other variables.

This report concentrates on annoyance directly associated with acoustic exposure, rather than annoyance produced as an indirect consequence of other effects of noise on people.

1.4 Approach to Modeling Annoyance

The USAF's environmental assessments must deal with noise-induced annoyance produced both by isolated noise intrusions and by multiple operations, as well as with the annoyance of both individuals and communities. As tidy as it would be to examine both individual and community annoyance caused by single noise intrusions and aggregate exposure in identical terms, the levels of analysis most appropriate to the two forms of annoyance differ sufficiently to make separate models desirable. Accordingly, a model for community annoyance engendered by long term exposure to multiple noise events is developed in Chapter 2, and one for the annoyance of isolated noise intrusions is developed in Chapter 4. The former model is most relevant to airport noise, while the latter is more relevant to the sort of noise exposure produced near an MTR.

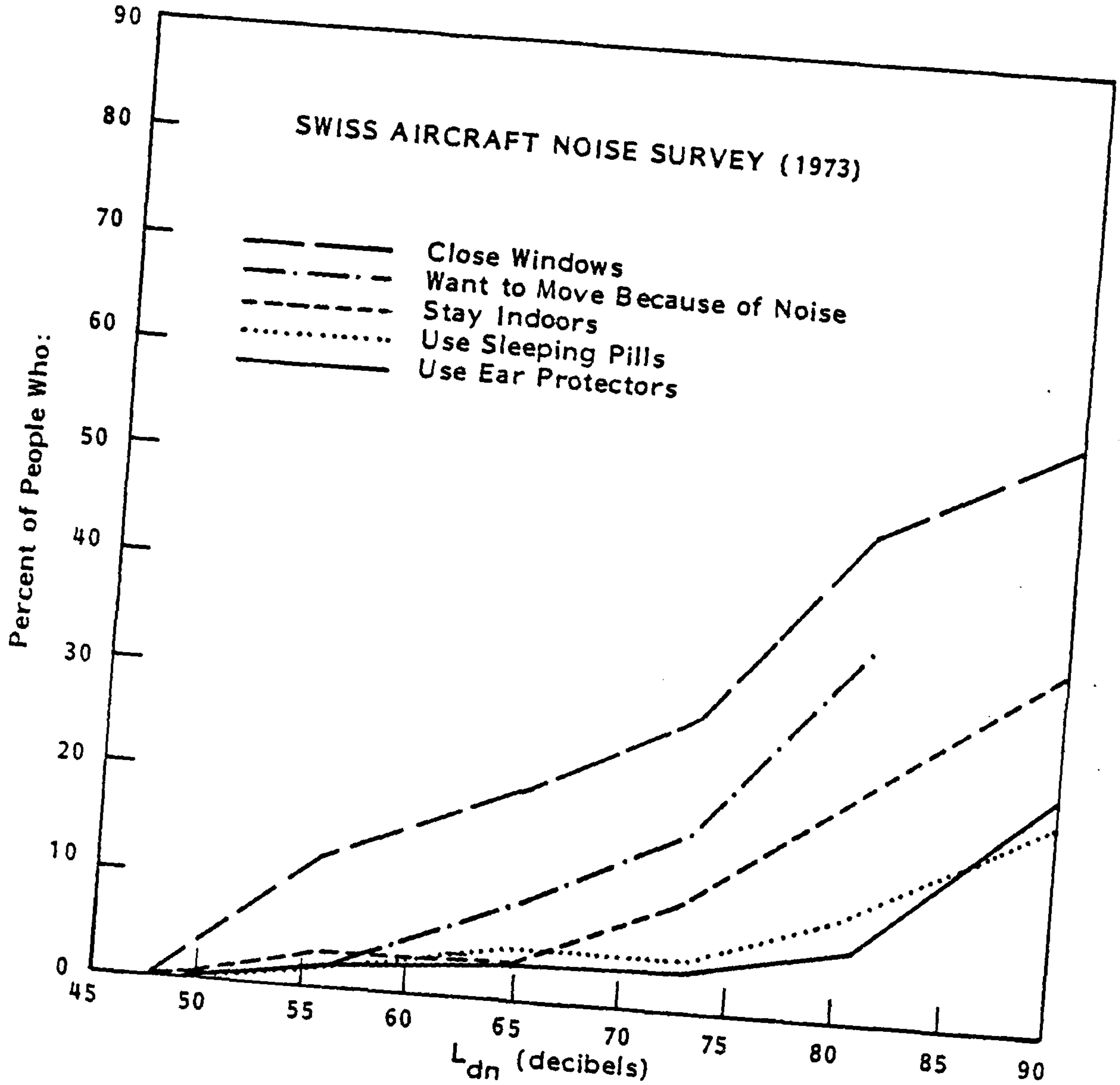

Figure 1-3: Behavioral Reaction to Aircraft Noise

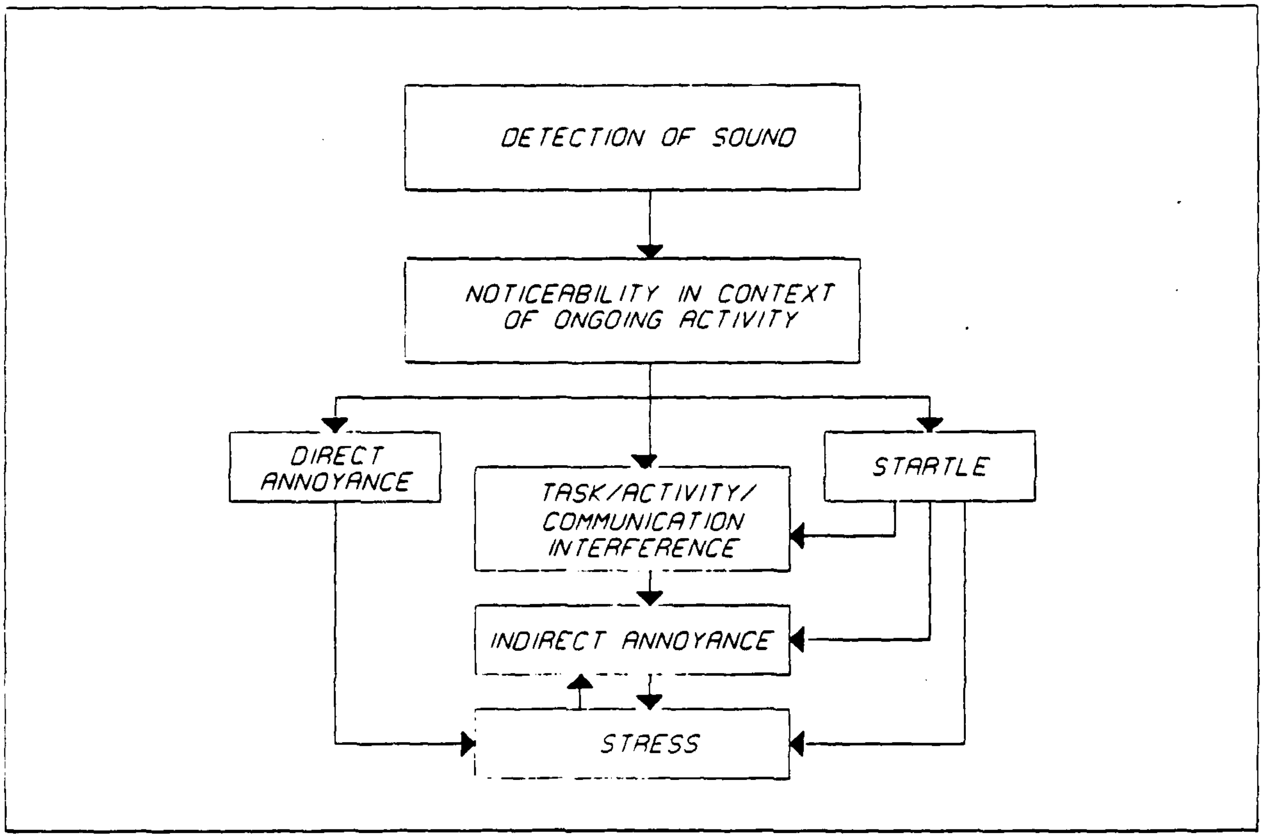

Figure 1-4: Simplified Model of Effect of Noise Exposure on People

2. DEVELOPING A MODEL FOR COMMUNITY ANNOYANCE

The purpose of this section is to develop a model for the aggregate annoyance of multiple noise intrusions to populations of individual. The model will serve as a theoretical underpinning for the empirical dosage-effect relationship derived by Schultz (cf. Figure 1-1). Readers who are not familiar with the nature of indoor and outdoor noise exposure in residential neighborhoods may find it helpful to read Appendix B before continuing.

2.1 Model Development

The initial problem in developing a systematic understanding of Schultz's dosage-effect relationship is in characterizing the effective noise burden of individuals. As noted in Appendix B, long-term exposure to the distant and local components of a residential noise environment produces different noise "doses" in different individuals. Noise doses vary because different people spend different amounts of time at home, and because not all residences in a neighborhood are exposed to identical noise levels from all local noise sources. It is therefore reasonable to regard the noise exposure suffered by any particular resident as a random variable associated with a noise dose.

A noise dose can in turn be treated as a parameter of the probability distribution from which the random variable is drawn. Each individual's reaction to a noise dose can be considered a random sample from this probability distribution. A neighborhood resident can be assumed to become "highly annoyed" when the individual noise dose exceeds a threshold level. The percentage of individuals in a residential population who are highly annoyed therefore depends on the probability that individual doses exceed a threshold.

Two transformations are needed to bridge the gap from the level of residential noise exposure to the prevalence of annoyance. The first transformation converts a physical measure of outdoor noise levels to a personal noise dose. The second transformation converts dosage to the probability of annoyance. Although the first transform requires a choice of metric for physical noise exposure, the choice of any particular metric does not affect the generality of the model. For the sake of consistency with federal policy, the preferred noise metric is the DNL.

The first substantive assumption is that a given outdoor exposure, ultimately to be specified in terms of DNL, generates an exponential distribution of individual noise doses. The exponential distribution is assumed both for the sake of simplicity (it is completely characterized by a single parameter) and for mathematical tractability. As with the choice of exposure metric,

the distribution assumption does not affect the generality of the theory. Thus, noise exposure can be represented as a continuous random variable, with a probability density written for $x > 0$ as

$$f(x|L) = 1/b(L)\ \exp\ (-x/b(L)), \tag{1}$$

where: x is an individual's noise exposure
L is physical exposure level and
b is the noise dose.

Dosage is assumed to be a monotonic function of the physical exposure level, L. Equation 1 relates levels of exposure, and ultimately the probability of being annoyed, to a monotonically increasing function of exposure, b(L), and an assumed distribution function -- in this case, the exponential. Higher levels of exposure, L, create higher levels of dosage, b(L), which create higher probabilities of annoyance. The assumption of an exponential relationship between outdoor noise levels measured at a fixed place and the personal noise dose implies that most people receive a noise dose lower than that recorded by the microphone; that a few hear almost as much noise as the microphone; and that the probability that an individual's noise dose will exceed that measured by the microphone is very small.

Without loss of generality, it can be assumed that the dose associated with the distant component of a neighborhood's ambient noise distribution (see Appendix B) has a value of unity ($b = 1$). Thus, without intruding noise sources, the noise exposure associated with the distant component of neighborhood noise distribution can be written as

$$f(x|\text{ambient noise exposure}) = \exp(-x)\ \text{for}\ x>0 \tag{2}$$

It is probable that certain noises that are part of the distant component of a neighborhood noise environment can generate an exposure sufficient to induce annoyance. However, the probability that the distant component of the ambient noise process can generate exposures sufficient to induce some consequential degree of annoyance is quite small. More specifically, it is assumed that an exposure, x, must exceed some criterion level, K, before it produces what Schultz considers "high" annoyance. It seems reasonable to assume that the value of K adopted by most people in a community is sufficiently great that it is rarely exceeded by a noise exposure associated with the distant component of the ambient noise distribution.

Calculation of the probability that a particular noise exposure, x, leads to high annoyance is straightforward. This probability is simply the integral of the probability density, f(x), above the criterion level, K:

```
P(High Annoyance) = integral from K to inf f(x)dx   (3)
```

For the assumed exponential distribution with mean b(L), this probability is thus

```
P(High Annoyance) = exp (-K/b(L))                   (4)
```

2.2 Sample Calculations

The ideas presented above can be illustrated more concretely by assuming a specific threshold value, K. For a threshold value of 5, the probability of high annoyance arising from the distant portion of the ambient distribution of neighborhood noise alone (i.e., for b(L) = 1) is only 0.0067. For a noise dose ten times greater, b(L) = 10, the probability of high annoyance is 0.606, and for a noise dose still ten times greater, b(L) = 100, the probability of high annoyance is 0.951. Thus, over a ratio of noise dosages of 100:1 (20 dB), the probability of high annoyance varies essentially from 0 to 1. These assumptions provide a basis for relating the noise dosage, b(L), to the probability of high annoyance associated with that dosage.

The remainder of this discussion focuses on the relationship between the noise dose, b(L), which is the mean of the assumed exponential distribution and a particular physical metric, L. Since the immediate goal is to derive a theoretical relationship comparable to Schultz's empirical relationship, DNL is the obvious choice of basic exposure metric. Further assumptions are needed, however, to transform outdoor equivalent sound pressure measurements into an "effective" noise metric.

An attractive first approach to defining an "effective" noise metric is to assume that b(L) is related to the psychological effect of the acoustic energy generated by exposure to noise. Two implications of this assumption are: 1) that it is not the magnitude of noise energy per se that induces annoyance, but rather its perceived magnitude to human observers; and 2) that it is only the noise energy exceeding some threshold of noticeability which contributes to annoyance.

It is therefore further assumed that a compression function is necessary to model the apparent magnitude of the acoustic energy of noise exposure. According to Stevens (1975), the apparent loudness of simple sound exposure is proportional to the 0.3 root of acoustic energy, or the 0.6 root of sound pressure. Thus, it is assumed for our purposes that b(L) is proportional to the equivalent energy of noise exposure, raised to about the 0.3 power.

Following the suggestion of Gjestland et al. (1987), a threshold of effect is also needed to discriminate noise exposure that actually contributes to annoyance from noise exposure that is not loud enough either to be heard by residents or to be noticed if it is audible. Writing this

$$b(L) = \exp[\ (L_{dn} - T)\ /\ S\ ] \qquad \text{for } L_{dn} > T \qquad (5)$$

where: T is a threshold value for effective noise exposure, and S is a scale factor.

A reasonable threshold value to assume for our purposes is a DNL of 55 dB, a level that has been identified by the Office of Noise Abatement and Control of the U.S. Environmental Protection Agency as a standard to protect public health and welfare with an adequate margin of safety (EPA, 1974). The scale factor, S, is then the only remaining free parameter of the model and can be arbitrarily chosen to compare theoretical predictions with Schultz's empirical results. The value of S = 12.2 provides a fairly good fit to the third-order polynomial derived by Schultz as a descriptive dosage-effect relationship. Such a value for the parameter S confirms a compression of sound energy to the 0.3559 power, a value in reasonable agreement with Stevens' suggestion of 0.3.

Equations 4 and 5 can be used in conjunction to express the probability of high annoyance as a function of the physically measurable exposure parameter as follows:

$$P(\text{High Annoyance}) = \exp\{-K \exp[\ (-L_{dn} - T)/S\ ]\} \qquad (6)$$

The curve plotted along with Schultz's relationship in Figure 2-1 is produced by using the following values: K = 5, T = 55 dB, and S = 12.2. The rms difference (one measure of error of prediction) between Equation 6 and Schultz's relationship is less than 7% over the range of DNL values from 55 to 75 dB. The theoretically derived predictions fit well within the range of 90% of the empirical data throughout this range of DNL values as well.

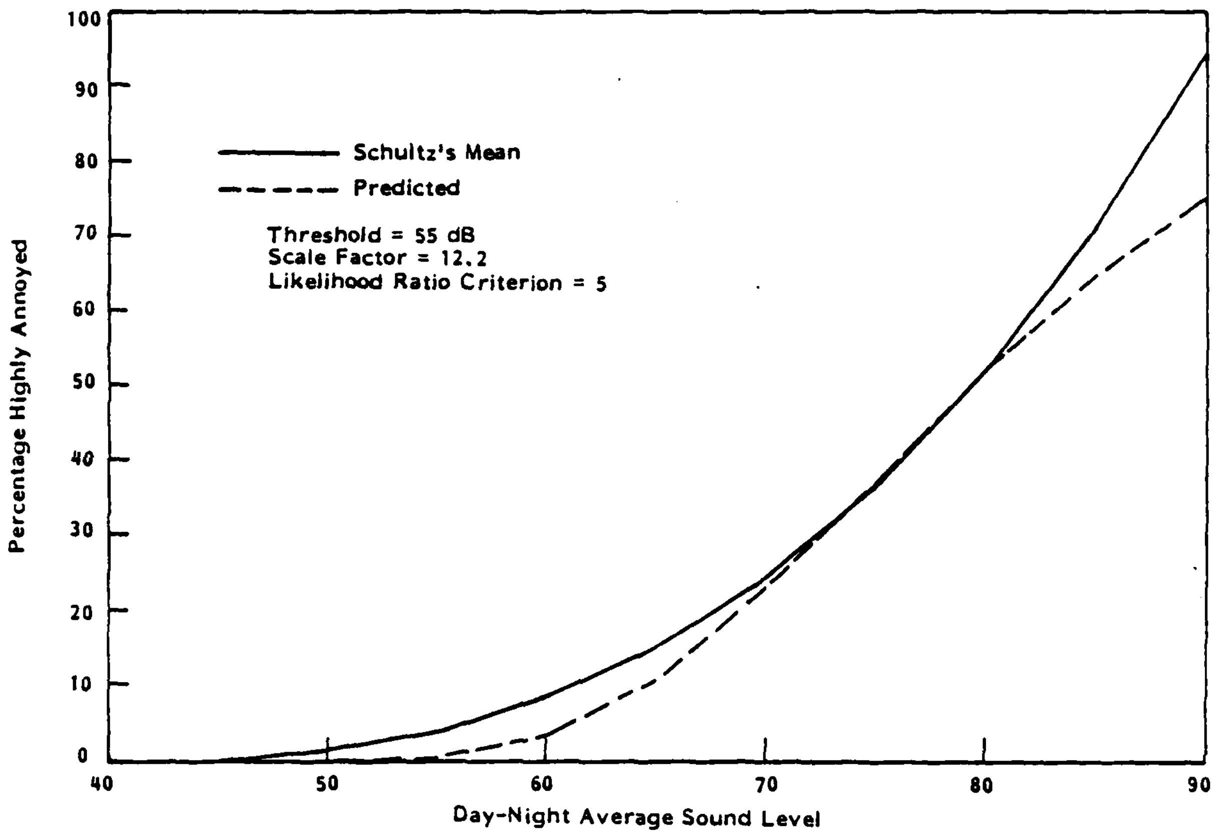

Figure 2-1: Comparison of Dosage-Effect Relationship Derived by Schultz (1978) with Current Exponential Model

In fact, the major difference between the empirical and theoretical relationships in Figure 2-1 is their shape, not their proximity to any of the social survey data points. For convenience, Schultz used a third order polynomial to fit the empirical data, producing a positively accelerated curve over the plotted range. Although useful for fitting arbitrary data points, this type of positively accelerated function has no useful interpretation in expressing the prevalence of annoyance.

In reality, the graphic relationship between noise exposure level and the prevalence of annoyance is almost certainly sigmoidal in shape, with asymptotic values near 0% and 100% at extreme noise exposure levels. Because some people do not report high annoyance even at very high exposure levels, the negative acceleration at high exposure levels seen in the theoretically predicted relationship in Figure 2-1 is preferred on common sense grounds to the polynomial fit developed by Schultz for curve fitting purposes.

It is interesting before leaving this topic to explore how variation in the criterion for reporting high annoyance (i.e., variation in the parameter K) can account: 1) for variation in the response of different populations to the same noise exposure, and 2) for variation in response by the same population to different noise exposures. While the value of $K = 5$ is a reasonable choice of the threshold parameter, it was selected largely to produce a low rate of highly annoyed individuals (less than 1%) for noise exposure produced by the distant component of the distribution of ambient noise in residential neighborhoods. It is quite possible that the value of the criterion for reporting annoyance, K, can be manipulated, perhaps through efforts to change how people perceive the appropriateness of certain noise intrusions.

Holding the values of T (55 dB) and S (12.2) constant, Figure 2-2 shows how variation in K over a range of 16:1 affects the percentage of people highly annoyed. This range of about 12 dB in threshold values produces predictions that cover virtually all the survey data considered by Schultz in his review.

Such a change in the value of K offers a simple and straightforward explanation of the differences between dosage-effect relationships that have appeared in the noise effects literature (cf. Appendix A). It is not necessary to assume that annoyance causally produced by aircraft noise exposure differs in two communities with different observed prevalences of annoyance. It may well be that such communities differ only in the average K value for reporting annoyance.

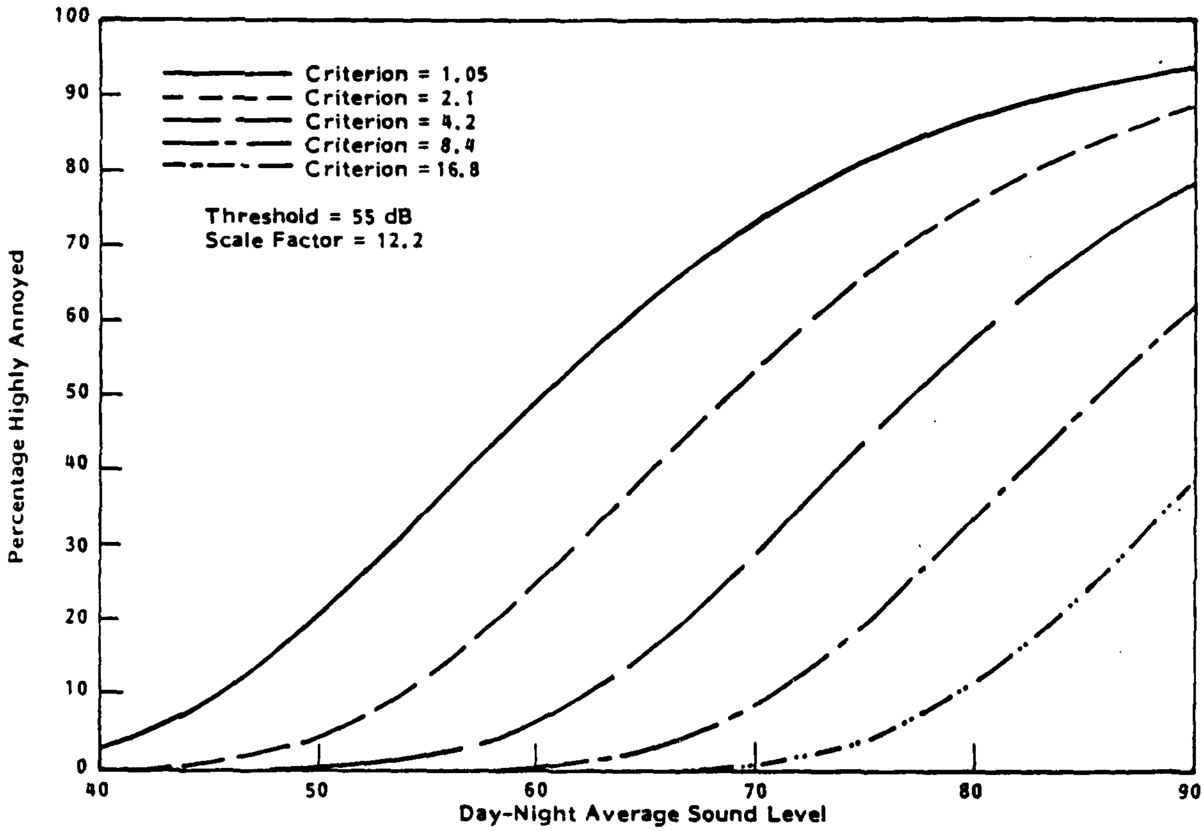

Figure 2-2: Effect of Changing Criterion for Reporting High Annoyance on Dosage-Effect Relationship

2.3 Dynamic Aspects of Community Annoyance

An important aspect of annoyance that has been ignored thus far is the manner in which variation in the level of noise exposure affects community reaction. Both the short and long term aspects of exposure dynamics deserve discussion. The long-term aspects are examined first.

Noise exposure has been characterized so far in terms of the acoustic energy (DNL) greater than the threshold value, 55 dB. This descriptor was chosen because it is relatively simple, and because it is consistent with present federal policy. Suppose the exposure changes its mean value because of a sudden increase in noise (some new construction activity or a change in airport activity). How soon and at what rate will the community react to such a change.

There has been very little research on this topic. Most models of community annoyance, like this one, are essentially static. The most extensive data on this issue came from a study by Fidell, Horonjeff, Mills, Baldwin, Teffeteller and Pearsons (1985). Fidell et al. surveyed community reaction at four different times during changes in flight path operations at a local airport. The percentage changes of highly annoyed judgments were modeled with a simple exponential equation. Estimating the model parameters was difficult because only four temporal points were available.

Nonetheless, the estimated time constants suggested rather long integration times (ranging from 25 - 1,600 days). The two neighborhoods experiencing a decrease in noise level showed the largest time constants. The authors concluded "at least tens of days must elapse before short-term attitudes about changes in noise exposure develop into long-term attitudes".

With this model there are several ways to account for changes in parameter values with changes in noise exposure. The simplest way to incorporate dynamic effects is to assume that changes in noise exposure affect the reference noise distribution, which would lead to a new K value. More detailed quantitative data must be obtained before any specific alternative could be adopted.

A second aspect of changing noise exposure, involving short term changes, concerns how varying noise levels affects the calculation of noise exposure within the model. This model assumes both some form of energy integration (via DNL, albeit at different discount rates in the day and night) as well as a threshold value, T. As Gjestland and Oftedal (1980), who first promoted the idea of energy accumulation modified by a threshold observed, the threshold value has a sizeable influence on the temporal distribution of effective noise exposure. Experimental data have confirmed that temporal distribution of noise exposure can influence annoyance judgments, even when the exposures are equated for total noise energy (Gjestland and Oftedal, 1980; Gjestland, 1987; Cermak, 1979).

In this initial formulation the dynamic aspects of noise exposure have been ignored; the only adjustment to noise exposure as measured by DNL is the assertion of a 55 dB threshold of effect. Assumption of any threshold of effect does however influence the apparent temporal distribution of noise exposures that contributes to the total noise dose.

3. BASIS FOR THE INDIVIDUAL NOISE EVENTS ANNOYANCE MODEL

Although the model developed in the preceding chapter provides a simple explanation for differences in the growth rates of the prevalence of annoyance in communities with similar noise exposure, it does not provide a detailed understanding of how acoustic and nonacoustic variables contribute to the annoyance of individual noise intrusions. This chapter discusses fundamental issues which distinguish acoustic from nonacoustic influences on annoyance, and lays the groundwork for the development of an annoyance model for individual events appearing in Chapter 4.

3.1 The Conventional View of Annoyance

It is convenient for the sake of exposition to describe the conventional view of annoyance in strawman terms. In this oversimplified view, a noise source creates "unwanted" sound (sound that is too inconvenient or too expensive to control), which propagates through the environment to an observer's ear, whereupon it is transduced into neural energy. This neural energy is compared in a deterministic but mysterious way against an internal, unidimensional scale to produce an annoyance "rating".

Acousticians, engineers, and other psychoacoustic practitioners have generally regarded events that occur after noise energy arrives at the eardrum with unease, and have been correspondingly reluctant to offer explanations for them. These internal events are nonlinear, complex, and lack straightforward input-output descriptions.

The study of annoyance-related phenomena occurring outside the eardrum has thus been viewed as safer than the study of annoyance-related phenomena occurring on the other side of the eardrum. The conventional means of measuring annoyance, whether in the laboratory or in the field, have therefore been atheoretical by tradition. It is useful at this point to review some of these standard methods.

A typical way to measure the annoyance of sounds in a laboratory setting is to present a set of sounds to a group of test subjects who are instructed to rate the annoyance of the sounds in any of a variety of ways. The more common laboratory techniques for eliciting annoyance judgments include paired comparisons (presentations of sounds in pairs -- one constant, one variable in some fashion -- to elicit relative judgments); category scaling (assignment of sounds to a fixed number of labeled classes); and magnitude estimation (assignment of numeric values

to sounds), sometimes with reference to thermometers or clock faces or even arbitrary numeric estimates, to elicit absolute judgments.

Less common laboratory methods for eliciting annoyance judgments range from cross-modality matching ("squeeze this ball as hard as the sound is annoying"), to semantic differentials (descriptions of multiple subjective attributes of sounds), to behavioral avoidance schedules (permitting subjects to escape exposure by some operant response). Instructions provided to subjects range from none at all (Molino, 1974) to elaborate encouragements to imagine one's reactions as if the sounds were heard in one's own home (Kryter, 1963; Borsky, 1973). In some cases, living room mockups were employed to simulate a home environment (Borsky, 1973; Rice, 1977; Hubbard and Powell, 1981).

In a field setting, annoyance is gauged most often by absolute judgment category scales. Respondents are asked to pick a category label corresponding to their degree of annoyance with a particular noise source from among five (or two or seven or forty-five or more) labels. Typical wording for a questionnaire item on annoyance is "Have you been bothered or annoyed by (noise source) over the past (time period)?". Occasionally this form of direct self-report is complemented or replaced by indirect scales of annoyance, constructed from combinations of responses to questions dealing with specific noise effects (speech interference, sleep interference, etc.).

Regardless of the technique used to elicit annoyance judgments, the next step is inevitably an effort to regress a physical measurement of some attribute of noise exposure on the set of subjective judgments. The range of acoustic properties that has been used to predict annoyance is a tribute to the collective imagination of several generations of researchers. In addition to many different frequency weighting schemes, the physical properties thought to be useful in predicting annoyance have included tonality, impulsiveness, rise time, periodicity, time of day, and temporal variability. Pearsons and Bennett (1974) and Schultz (1972, 1982) among others have cataloged dozens of physical measures of sound that have been seriously considered as predictors of the annoyance associated with noise exposure.

The quest for metrics of annoyance reached its peak in the years following passage of the Federal Noise Control Act of 1972. This quest, funded in large part by federal agencies and the aviation industry, diminished in intensity only after the DNL gained widespread acceptance as an omnibus metric of environmental noise exposure.

Two observations may be made about the conventional approaches to measuring annoyance outlined above. The first observation is that all the acoustic metrics suggested for quantifying annoyance correlate highly with each other, if not with self-reports of annoyance (Fidell, 1984). The high correlation among the various noise metrics is the basis for a common view that the choice of metric for measuring aircraft noise is relatively unimportant. It is now generally

acknowledged that adoption of any reasonable noise metric for regulatory purposes would have been more productive than decades of research devoted to refining an optimal measure. It is for this reason that, a decade ago, all U.S. federal agencies concerned with environmental noise assessment agreed on the DNL for use as a general purpose measure of environmental noise exposure. It was such a sensible way to resolve the conundrum of routine environmental noise measurement.

The second observation is that a search for a universal, all-purpose noise metric is unlikely to succeed. There are as many ways to measure noise as there are purposes for the measurement. In the absence of an annoyance theory a search for an optimal acoustic measure of annoyance places the cart before the horse. The fundamental problem is not, after all, measurement, but rather deciding what is worth measuring. In this case, decades of psychoacoustic research have demonstrated that it is unreasonable to expect purely physical measures to provide a complete realistic account for the attitude of noise-induced annoyance.

As Isaac Newton remarked about the perception of color, the rays themselves are not colored (Wright, 1967). Following transduction of light to neural signals, human color perception is influenced by variables unrelated to the wavelength of the original electromagnetic disturbance of the retina. Likewise, the processes that lead to the perception of noise-induced annoyance are often unrelated to the original sound wave striking the eardrum. This implies, for example, that no matter how *convenient it is (for other purposes) to* express sonic boom overpressures in pounds per square foot, there is little hope of understanding human annoyance to sonic boom exposure in such units.

3.2 Issues Germane to a Theory of Annoyance

An alternative to the conventional study of annoyance is developed in the next chapter: a theoretically oriented approach intended to lead to a systematic understanding of annoyance. As noted earlier, block diagrams such as Figure 1-4 only hint at the relationships between noise exposure, annoyance, and other effects of noise on people. A useful theory of annoyance should provide a framework within which answers can be sought to a variety of questions about noise-induced annoyance, including the following:

- Why are some sounds annoying to some people, but not to others?
- Why are the same sounds annoying to people at some times, but not at others?
- What are the relative contributions of acoustic and nonacoustic factors to annoyance?
- What are the dynamics (i.e., the time constants of onset and decay) of annoyance?

Are intermittent or time varying noises more annoying than steady state noises? What is the minimally annoying way to distribute a fixed amount of noise exposure over a given time period? Why do people become habituated or sensitized to noise exposure?

- Is annoyance something other than duration-corrected loudness?
- Can publicity affect the annoyance of noise exposure?
- Do predictable episodes of noise exposure produce less annoyance than unpredictable episodes of exposure of the same magnitude?
- Does the ambient noise environment in which sounds are heard affect their annoyance?
- Do expectations about the appropriateness of noises heard under different circumstances affect the annoyance of noise intrusions?
- Why does the A-level of a sound serve as a partial predictor of its annoyance?

It is one thing to recommend a theoretical treatment of a phenomenon, but quite another to generate one. Before an effort is made in the next chapter to do so, the conventional approach to the study of annoyance described above only as only a strawman is re-examined in greater detail.

3.3 Re-examining the Conventional View of Annoyance

The black box approach to predicting annoyance described earlier is not entirely without merit, nor is it as completely atheoretical as it was portrayed. Even without explicit consideration of intervening variables between exposure and an annoyance "rating", this approach has succeeded in demonstrating the need for frequency weighting networks to account for relative annoyance judgments. It is instructive to trace the history of this accomplishment.

When the first formal environmental noise survey was undertaken in New York City in 1929 (Fletcher, Beyer, and Duel, 1930), it was realized that the bandwidth and frequency response of the noise measurement system had to be appropriate to the purpose of the survey. Since the purpose of the survey was to represent urban noise levels in terms relevant to the inhabitants of the city, it made little sense to measure the total acoustic energy in the city (including inaudible infrasound and ultrasound). By the same token, it also made no sense to accept the vagaries of the frequency response of available acoustic instrumentation as a useful measure of environmental noise.

The solution was to measure environmental noise through a filter network that reflected the newly discovered equal loudness contours (Fletcher and Munson, 1933). These contours

emerged from early audiometric studies that showed that people are not equally sensitive to sound energy at all audible frequencies. The Fletcher-Munson contours are level-dependent, however, so that different frequency weighting networks (later standardized as the A-, B- and C-weighting networks) were thought to be needed to evaluate noises of different levels. The present practice of making most environmental noise measurements through the A-weighting network (DNL is based on A-weighted sound level measurements) embodies the same principle.

The outlines of a theory can be discerned in this time-honored practice. If noise measurements are to be used for predicting their effects on people, then the units of measurement should reflect their audibility by human observers. Stated more baldly, the "theory" implicit in reliance on A-weighted noise measurements of aircraft noise exposure is that the only part of the aircraft's noise emissions that annoys people is the part they can hear. Furthermore, if frequency compensated sound pressure level is all there is to annoyance, then it follows that all other things being equal, all sounds of equal A-level should be equally annoying. Likewise, sounds of greater A-level should always be more annoying than sounds of lesser A-level.

What this theory lacks in sophistication and universality (not to mention correctness), it makes up for in simplicity and superficial plausibility. Generations of environmental acousticians and noise control engineers have grown up tacitly accepting this quasi-theoretical viewpoint. Unfortunately, frequency weighted noise metrics cannot be relied upon to provide a full account of annoyance data, nor do they have much explanatory value in and of themselves that can aid the understanding of community response to aircraft noise exposure.

3.4 Evidence Suggesting a Systematic Basis for Modeling Annoyance

Like many theories, the theory that annoyance is predictable by characterizing signal levels in terms of human aural sensitivity can be improved upon. For example, it has long been known (Wegel and Lane, 1924; Fletcher, 1938) that the background noise in which an acoustic signal is heard also influences its audibility. In the 1950's, Tanner and his associates developed a mathematically rigorous treatment of the effects of masking on acoustic signal detectability (Green and Swets, 1966). A number of demonstrations of the usefulness of detectability-based concepts in accounting for annoyance judgments are briefly described below.

3.4.1 Effect of Background Noise on Annoyance

One of the clearest demonstrations that the background noise in which a sound is heard affects the degree to which it is judged annoying was that of Fidell, Teffeteller, Horonjeff and Green (1979). The annoyance of 24 common environmental sounds was judged in three different background noise environments: one with a falling spectrum (typical of most outdoor urban noise environments), one with a flat spectrum, and one with a rising spectrum. The absolute A-weighted sound pressure levels of the test sounds varied by almost 30 dB. Because the different background noise environments masked different spectral regions of the various sounds differentially, the same sound heard at the same level was differentially detectable and differentially annoying in the different background noise conditions.

Fidell et al. found that the predicted detectability of the set of sounds accounted for almost 90% of the variance in annoyance judgments made in the most commonplace (falling spectrum) background noise environment. They also found that the usual frequency weightings (A-level, Perceived Noise Level, Overall Sound Pressure Level, Loudness Level, etc.) did no better than an index of detectability in accounting for variance in the two other unusually shaped background noise environments.

Johnston and Haasz (1979) have also reported the findings of a laboratory demonstration in which the background noise in which aircraft flyovers are heard influences their annoyance. Johnston and Haasz showed that a reduction in background noise of about 20 dB was equivalent to increasing the annoyance of a flyover by 5 dB. Unfortunately, they do not describe the frequency of the background or flyover noises in a manner that would permit detailed calculations of audibility.

3.4.2 Effect of Attention on Annoyance

In a later study, Fidell and Teffeteller (1981) demonstrated that test subjects engaged in an attention-demanding foreground task did not report noticing intruding sounds until they had a considerably higher signal-to-noise ratio than would be required for detection in a deliberate listening task. The intensity of subsequent annoyance judgments made by test subjects after the presence of an intruding noise was noted (but while the subjects were still engaged in an absorbing foreground task) and was directly proportional to the detectability of the intruding sounds. Figure 3-1, adapted from Fidell and Teffeteller, displays this relationship.

Half of the subjects first noticed an intruding sound when it attained a signal to noise ratio characterized by a value of $10 \log d' = 14$ dB. People not absorbed in another task can reliably distinguish a signal from noise when its detectability attains a value of $d' = 1$ or $10 \log d' = 0$.

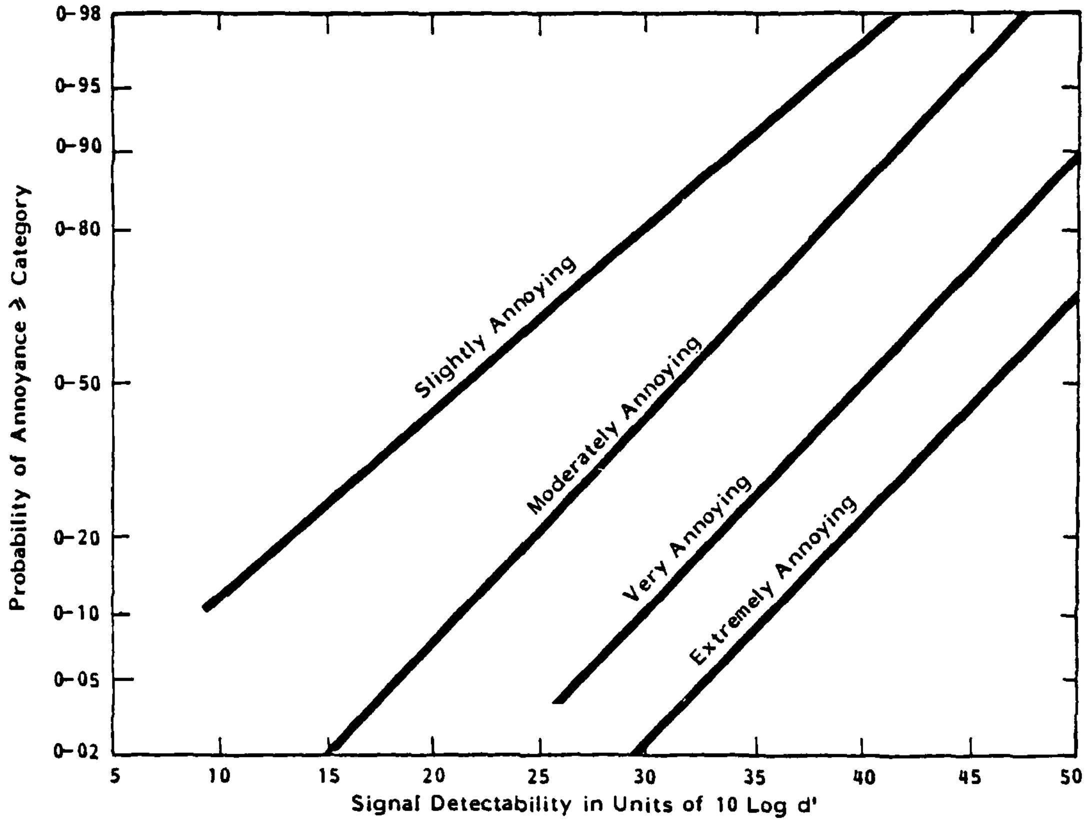

Figure 3-1: Relationship Between Annoyance and Detectability of Intruding Noises

Pearsons, Fidell, Horonjeff and Teffeteller (1979) found that subjects first noticed an intruding sound when not specifically listening for it at a value of d' = 2.3 or 10 log d' = 4 dB. The difference in results reported by Fidell and Teffeteller and by Pearsons et al. suggests that an absorbing task can have about a 10 dB effect on how people judge intruding sounds.

These data further led to the inference that the level of the detection index for an intruding sound (d') has to be three orders of magnitude (30 dB) greater than the barely audible level before 50% of the subjects, engaged in activities other than listening for the sound, are moderately annoyed. The data also suggest that intruding sounds have to be four orders of magnitude (40 dB) greater than the barely audible level before half the sample become extremely annoyed.

3.4.3 Effect of Background Noise on Acoustic Privacy

Similar principles are involved in determining the degree of acoustic privacy that people require in their dwellings and workplaces. A privacy calculation procedure worked out by Cavanaugh, Farrell, Hirtle and Watters (1962) takes account not only of the acoustic isolation provided by the partition that separates two dwellings, but also the local background noise in the neighbor's premises. (Other important elements in this privacy design scheme are the amount of sound absorptive material in the receiving room, the vocal effort of the talkers in the source room, and the neighbors' expectations for privacy.)

This scheme has been updated and simplified by Young (1965) and subsequently used by Schultz (1978) to justify the use of A-weighted sound levels in the enforcement of noise control elements in building codes. In all these schemes, the fundamental concept is that noise intrusions must be discounted by the prevailing background noise.

3.4.4 Role of Background Noise in Community Noise Assessment

The common belief that a given level of intrusive noise is less disturbing in locations with high background noise than in quiet locations is embodied in a number of schemes for evaluating community noise, dating back to the original Composite Noise Rating (1953). It still appears in the current ISO standard for "Assessment of Noise with Respect to Community Response" (ISO R-1996).

3.4.5 Contemporary Research Related to Background Noise Effects

Researchers have also been attracted to detectability-oriented concepts in their efforts to account for annoyance judgments. Preis (1987), for example, believes that masking level should be one component of an adjustment to existing noise metrics to account for the intrusive character of certain noises.

Schomer (personal communication, 1987) among others suggests that three regimes can be identified for annoyance judgments. The first of these is for sounds which have relatively the same level as ambient noise levels. In this regime, Schomer believes that detectability-based indices of annoyance are most appropriate. The second regime is one in which noise levels are not significantly masked by the ambient environment, for which conventional integrated energy metrics may be most useful. The third regime is that of very high exposure levels, for which loudness-related metrics may be required. Residential exposure to such high levels of impulsive noise is often accompanied by "secondary emissions" such as rattling noises. Galloway (personal communication, 1986) has remarked on the similarity of the growth functions for loudness and community response at high absolute exposure levels.

3.4.6 Effect of Ambient Noise Environment on Integrated Exposure Metrics

Gjestland and Oftedal (1980) and Gjestland (1987) have introduced the concept of calculating environmental noise exposure for purposes of predicting annoyance with respect to a threshold, rather than as a continuous integration. Such an interrupted integration process can be viewed as an indirect means of incorporating detection-based concepts into noise metrics, since the only noise energy that contributes to the metric is that which exceeds some detectability threshold. Further applications of decision-theoretical constructs to effects of noise other than annoyance (e.g., sleep and speech interference) have also been made (Horonjeff et al., 1982; Fidell, 1984 and 1979).

3.4.7 Applications of Decision-Theoretical Concepts to Social Survey Data

Decision-theoretical concepts have also been applied to social survey data, in an effort to distinguish actual changes in annoyance (due to changes in aircraft noise exposure) from mere shifts in criteria for reporting annoyance. Interpretation of respondents' category scale judgments in social survey data is complicated whenever judgments are taken at different times. However, if the noise exposure is known for the same time periods as the annoyance judgments, then ROC (Receiver Operating Characteristic) analysis (see Appendix C) can be used to assess the stability of annoyance judgments, as shown by Fidell, Horonjeff, Mills, Baldwin, Teffeteller

and Pearsons (1985). Fidell et al. used an ROC analysis to show that the percentages of respondents describing themselves as "not at all" through "extremely" annoyed covaried with exposure. The changes in percentages of respondents selecting each response category were indexed by the d' metric to demonstrate a genuine relationship between changes in annoyance judgments and changes in noise exposure, rather than a simple temporal shift in response bias.

3.4.8 Summary of Evidence

Evidence that *detectability strongly* affects annoyance suggests that a decision-theoretical approach to modeling annoyance is promising, especially for the case of intruding noise sources heard in a residential setting. Chapter 4 develops such an approach.

4. A DECISION-THEORETICAL APPROACH TO MODELING THE ANNOYANCE OF INDIVIDUAL NOISE EVENTS

Just as dozens of physical metrics have been proposed as potential annoyance predictors, a variety of factors have been championed by different researchers as annoyance determinants. Most of these putative determinants have been identified from atheoretical analyses, often as the predictor variables emerging from multiple regressions on individual data sets. Few have been shown to have predictive value for data sets other than those from which they were derived.

Some of these predictor variables are surrogates for demographic and socioeconomic (lifestyle) factors -- for example, age, sex, population density, social status, and income. In one *reductio ad absurdam* example (Tracor, 1971), the city in which an airport was located was identified as a predictor of the prevalence of aircraft noise annoyance. Other variables sometimes thought to predict the prevalence of aircraft noise annoyance include attitudes toward noise sources and their operators, fear of aircraft crashes, the apparent controllability and locus of control over the operation of a noise source, beliefs in malfeasance, and so forth.

Although some of these variables probably do have some predictive value under some conditions, the absence of a coherent conceptual framework for them makes it virtually impossible to specify in advance which ones are salient in any particular setting. Their usefulness for explanatory or predictive purposes is therefore limited by their lack of integration into a systematic framework.

The goal of this section is to construct a systematic account of the relationship between the detectability of a noise intrusion and its annoyance. To accomplish this goal, factors that determine the detectability of noise intrusions must be addressed first. These include most notably the relative frequency of the noise intrusion, the frequency of the background noise distribution, and the duration of the noise intrusion. The roles of a number of nonacoustic variables must also be specified. These variables include the probability of occurrence of noise intrusions, the values and costs associated with annoyance decisions, and the momentary state of individual listeners.

A brief digression is needed first to clarify the present strategy for reaching the above goal.

4.1 Prescriptive versus Descriptive Theories

Use of A-weighted sound level measurement to predict annoyance is a good example of a purely descriptive theory. It offers a metric for describing the relative annoyance of various noises without any supporting rationale or serious understanding of annoyance. When noises of equal A-level are not equally annoying, however, the theory provides little insight into the nature of the discrepancy. The instinctive response to such a failure of prediction is to suggest a different variable to account for ill-behaved data. As one *ad hoc* variable after another fails to give a satisfactory account of annoyance data, other variables are suggested as replacements.

A prescriptive theory, on the other hand, focuses not on what might happen in any particular circumstance, but rather on what should happen under ideal circumstances. For example, the relationship S = 1/2 GT**2 expresses a prescriptive law of gravity: the distance traveled by an object in free fall equals one half the product of g (a constant reflecting the acceleration due to gravity) and the duration of the fall (in seconds). The equation does not, by itself, predict how far a particular leaf will fall from a particular tree in any given period of time. Instead, it quantifies the underlying lawful relationships among time, distance, and the gravitational constant that are claimed to hold only for objects falling under certain idealized conditions.

The advantage of the prescriptive approach in this context is that it focuses attention on fundamental relationships between noise exposure and annoyance, rather than on the myriad variables that inevitably cloud these relationships in everyday settings. The goal of the prescriptive approach is not to compile an exhaustive list of all variables which might influence annoyance, but rather to identify the major variables and their interactions so that a useful amount of variance can be predicted in the general case.

4.2 Application of Decision-Theoretic Annoyance Concepts

The first part of this subsection outlines a prescriptive model of annoyance produced by exposure to individual noise events. The next subsection discusses the variables suggested by this model in greater detail. Two sets of concepts require understanding before the model is presented: 1) the nature of environmental noise exposure (particularly in residential settings); and 2) human decision making under conditions of uncertainty and risk. The reader who is not familiar with these concepts may profit by reading Appendices B and C.

4.2.1 Description of Model

4.2.1.1 Annoyance as a Decision-Like Process

Figure 4-1 is a schematic representation of a decision-theoretic approach to modeling the annoyance created by a noise intrusion. A verbal report of annoyance ("That sound is annoying") is viewed as the result of a decision-making process similar in structure to a decision about whether a sample of environmental sound contains noise alone or whether the sample contains both noise and a signal. This decision process lies at the root of all detection tasks.

The optimal way to decide between these two alternatives (whether a sample of sound is composed of noise alone or signal plus noise) is to determine a likelihood ratio for the noise, by calculating the ratio of two probabilities: 1) the probability that the sample, x, was drawn from a "signal plus noise" distribution, $f(x|sn)$; and 2) the probability that the same sample was drawn from a "noise alone", distribution, $f(x|n)$. In symbolic terms, this ratio is

$$L(x) = f(x|sn) \;/\; f(x|n), \tag{7}$$

where: $L(x)$ is the likelihood ratio of a particular sample, x.

As a technical detail, one should note that the sample, x, could be represented by a very complicated descriptor of the noise event. For example, x might be a vector, where the components of the vector describe the level of the noise at various time-frequency locations. Because the likelihood ratio is the ratio of two real numbers, however, it is a unidimensional scalar no matter how complicated the descriptor of the noise event may be.

4.2.1.2 The Nature of the Reference Distribution

In this application the distribution of noise alone is termed the "reference distribution", represented as Box 1 of Figure 4-1. The reference distribution is composed of all sounds regarded as a customary and proper part of a person's acoustic environment. The reference distribution to which people compare intruding noise events may change with location and activity. In the residential setting of greatest current concern, it is simplest to think of the reference distribution as the indoor noise distribution of the home. This distribution is composed of both internal noises of habitation and outdoor noises attenuated by the insertion loss of the home.

The concept of a reference distribution is fundamental because it provides the basis for

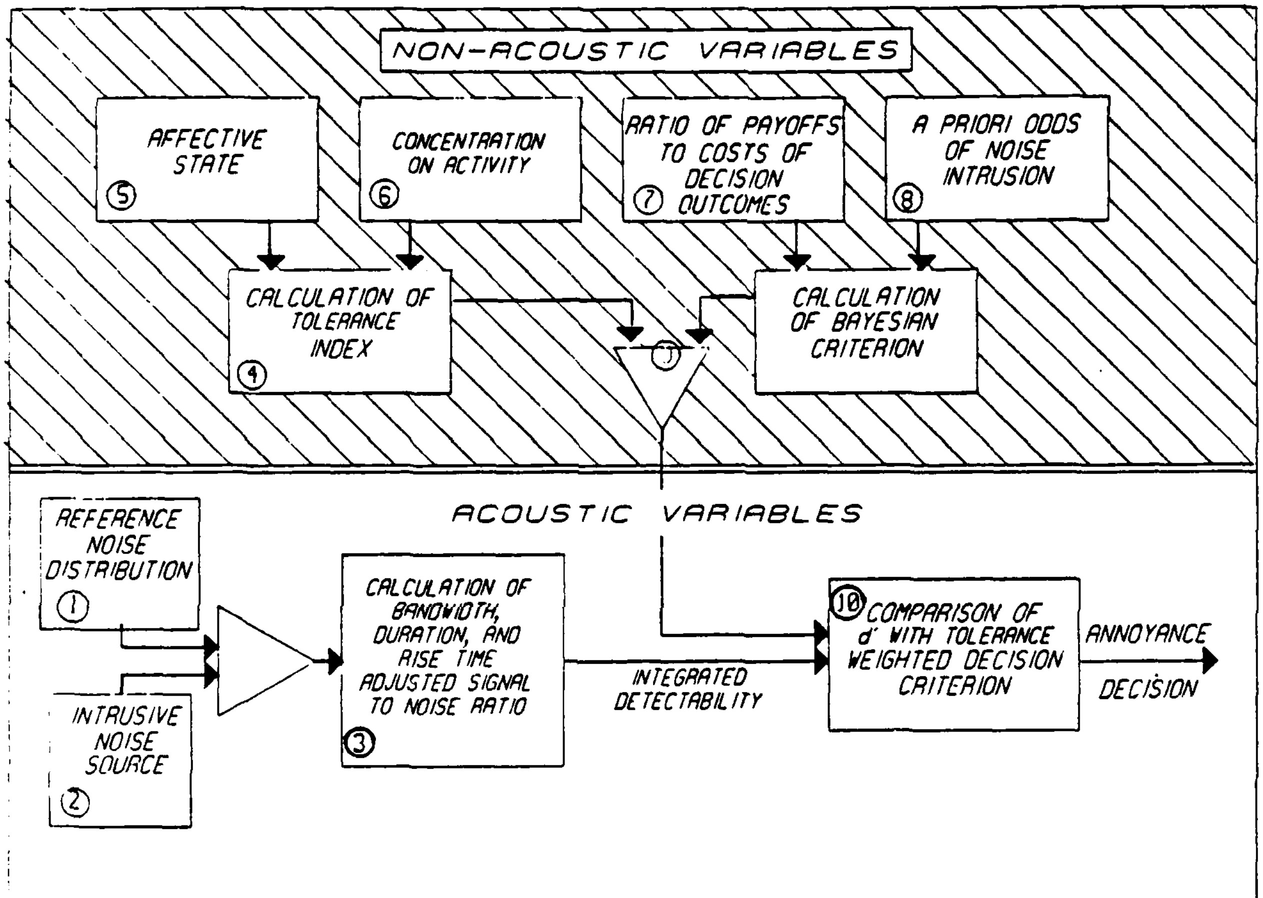

Figure 4-1: Schematic View of Decision-Theoretical Model of Annoyance Due to Individual Noise Intrusions

classifying as "intrusive" sounds whose probabilities of occurrence are small given this reference distribution. As explained below, decisions concerning whether intrusive sounds (represented as Box 2 of Figure 4-1 are annoying depend on the values of several nonacoustic variables.

The reference distribution is considered an acoustic variable because it can in principle be estimated with reasonable accuracy from physical measurements. While the reference distribution may be situation specific, and may even differ for different people, general agreement can be expected about the ambient noise distributions typical of residential, vocational, recreational or other environments. More important, it is possible with physical measurements to develop reasonable ranges of variation that can occur in these diverse environments.

As will become clear, the effect of the reference distribution on the annoyance decision making process is to modify the probability of classifying a noise event as intrusive, rather than to change the criterion of annoyance per se.

4.2.1.3 *Differences Between Detection and Annoyance Decisions*

Although decisions about the annoyance of intruding sounds resemble decisions about the detectability of such sounds, they differ in one important respect. In the case in which people are purposefully attempting to distinguish weak signals embedded in noise, it is common for the variances of the noise alone, and signal plus noise distributions to be similar. In this case, however, the variability associated with the distribution of intrusive noises may be much greater than either the mean or the variance of the reference distribution for annoyance judgments.

For example, the reference distribution within the home may have a standard deviation of only a few dB. Sounds of indoor and outdoor origins that intrude upon this reference distribution may vary by 60 dB (a factor of 1,000,000:1) or more. For reasons described in greater detail in Appendix D, this enormous variability in the level of intruding noises makes it convenient to assume that people make annoyance decisions by classifying as "annoying" any intrusive sounds that exceed a criterion level of the reference distribution alone, not on the basis of a criterion relating the reference and intruding noise distributions together.

It is important to clarify this difference between the likelihood calculation of detection theory and the threshold character of the annoyance judgment. Likelihood ratio is an efficient basis for detecting signals of low and moderate signal to noise ratio because it adjusts the detection criterion to take advantage of predictable signal characteristics. All other things being equal, decision criteria based on likelihood ratio are generally located at some point between the means of the distributions of noise alone, and the distributions of signal plus noise.

This strategy for placing the decision criterion permits people to adopt a relatively low

criterion for signals of low signal to noise ratio, but a much higher criterion for signals of greater signal to noise ratio. As a consequence, when signal to noise ratio increases, the probability of a correct detection (hit) increases and the probability of a false alarm decreases. A criterion set in this manner is said to satisfy a "minimax" strategy that both minimizes false alarm (and the costs associated with them) and maximizes hits (and the payoffs associated with them).

In the case of annoyance decisions, the magnitude of an intruding signal is virtually unpredictable, given the potentially large number of noise sources of different types operating at various times and distances from any given listener. As a consequence of this variability, intrusive signals have some composite (perhaps tending toward rectangular) distribution that ranges over practically all possible sample values. Thus, from a practical point of view, annoyance decisions might as well be based on a fixed decision criterion: one that is affected only by the familiar statistics of the reference distribution, rather than on one that is sensitive to the largely unpredictable statistics of the distribution of intruding noises.

The practical advantage of fixing an annoyance decision criterion with respect to the reference distribution alone is that the probability of a false alarm can be held constant at some low value, while the probability of a hit can increase as the level of the intrusive event increases. In other words, basing the decision criterion for an intrusive judgment on the statistics of the reference distribution alone, permits the probability of judging high-level intruding sounds as annoying to be greater than the probability of judging low-level intruding sounds as annoying, without any attendant increase in the probability of false alarms. This strategy (maintaining a constant false alarm rate without regard for the hit rate) is known in the decision theory as a "Neyman-Pearson" strategy.

The calculations represented in the third box of Figure 4-1 determine the integrated detectability of the signal with respect to a reference distribution. These calculations determine the frequency- and time-weighted energy of the acoustic event. A specific sound pressure level is established as a threshold with a given d' value, and all sounds producing a value above this level are classified as "unlikely to be part of the reference distribution"; that is, they are intrusive noise events.

4.2.1.4 The Rule for Determining Whether Intrusive Sounds are Annoying

The level of the intruding event (a detectability level) is compared with a criterion in Box 10 to determine if the event is considered annoying. This criterion is affected only by nonacoustic variables, represented by the boxes in the top part of Figure 4-1. These are assumed to be two distinct types. There are general state variables of the listener, as shown in Boxes 5 and 6. These two variables are combined into a tolerance index that modifies the decision criterion derived from strictly Bayesian decision criteria (i.e., those considered in Boxes 7 and 8).

In this context, "affective state" (Box 5) is a generic term that refers to an individual's mood and attitude toward the noise source at the time a noise intrusion occurs. Common experience indicates that people are not always equally tolerant of noise intrusions. Even when they are not occupied in any overt activity, people may for a variety of reasons react more strongly to noise intrusions at some times than at others.

"Concentration on ongoing activity" (Box 6) is used as a general term to describe the sensitivity to disturbance (distraction, interference, disruption of attention, etc.) of the activity a person is engaged in at the time a noise intrusion occurs. The consequences of noise-induced failures of performance are specifically excluded from this term, since the focus of this model is on noise-induced annoyance per se, rather than on the indirect annoyance associated with task interference.

4.2.1.5 Utility of a Tolerance Index

The assumption of a tolerance index serves two purposes. First, because affective state and concentration on ongoing activity are completely independent of acoustic factors, they provide mechanisms for explaining: 1) why the same acoustic signal does not always provoke the same intensity of annoyance at different times in the same individual, and 2) why different individuals may find the same signal differentially annoying.

Second, the role assigned to the tolerance index (as a modifier of the criterion value used to interpret whether an intrusive noise event is considered annoying) emphasizes the distinction between the independent influences of acoustic and nonacoustic factors on annoyance judgments. The acoustic factors are isolated completely in the detectability index computed in Box 3, which is used to determine whether a particular noise event is classified as intrusive or as part of a reference distribution. The nonacoustic factors influence only whether an intrusive event has sufficient magnitude to be classified as annoying, given the effective state of the listener.

4.2.1.6 Accounting for the Remaining Nonacoustic Variables

The remaining nonacoustic variables are the costs and payoffs associated with the outcomes of annoyance decisions (Box 7) and the *a priori* probability of intrusive noise events will occur (Box 8). In classical detection problems, these variables determine the value of the decision criterion for reporting the presence of a signal event. Formulae have been derived to calculate numeric values of these criteria for a variety of decision objectives. The effect of these variables in this theoretical treatment is complex, for reasons discussed below.

In conventional detection problems, costs and payoffs of decision outcomes and *a priori* probabilities of signal occurrence are known to exert considerable influence on detectors' hit and

false alarm rates. In this case, because the signal-to-noise ratio of an annoying noise event is often very large, its influence is often minor. This may be best seen in a simple example:

Suppose the detection problem is to distinguish noise alone from a fixed signal added to the noise. Assume also that the reference distribution is Gaussian, with unity variance, and that the signal increases the noise distribution by an amount, d'. The signal distribution is also assumed to have unit variance. Suppose the detector's strategy is to maximize the expected value of its decisions. As derived in Appendix D, for small signal values such as d' = 1 (common in conventional detection problems), changes in *a priori* odds can produce large changes in the likelihood ratio criterion and the resulting false alarm rate.

For values of d' between 1,000 to 10,000, however, where according to Fidell and Teffeteller (1981) annoyance judgments occur, the same changes in the *a priori* odds have essentially no effect on the response criterion. Thus, very large signal to noise ratios diminish the importance of the *a priori* odds and the costs and payoffs of decision outcomes as influences on the criterion for judging an intrusive noise event as annoying. This observation implies that different roles for the *a priori* odds and the costs and payoffs of decisions are appropriate for noise intrusions of different signal to noise ratios.

Decision-theoretic models tailored to high level aircraft noise intrusions (e.g., low altitude, high speed flyovers) may be able to ignore the effects of costs and *a priori* odds, whereas models tailored to low level noise intrusions (heel clicks in adjacent living quarters, plumbing noises, etc.) may have to pay more attention to these variables.

4.2.2 Deriving Quantitative Predictions from Model

Block diagrams and words help to describe the generalities of a theoretical model, but do not acquaint the reader with the relative importance of variables, sizes of effects, ranges of applicability, and so forth. These internal workings of the model are most conveniently illustrated in spreadsheet form. This subsection provides some of the specifics that are necessary to implement a model that can be manipulated in spreadsheet form to generate quantitative predictions.

4.2.2.1 General Assumptions About Acoustic Variables

The Reference Distribution

The first assumption that should be made explicit concerns the nature of the reference distribution, that is, the distribution of nonannoying noises. In principle, the statistics of this nonannoying distribution could be idiosyncratic to individuals based on personal experience,

expectations, or preferences. In other words, people might judge the intrusiveness of noises with respect to different reference or "ideal" distributions. However, to avoid dealing with ill-defined parameters, it is convenient in this case to assume that people are not annoyed by the indoor residential ambient noise environment. This environment contains both internally generated noises, as well as noises that are part of the distant component of the neighborhood noise distribution (cf. Appendix B).

People have freedom of choice in selecting living quarters: therefore, they may choose residential areas with different ambient noise distributions. It seems reasonable to assume that after living in a neighborhood for some period of time, residents become familiar with the statistical structure of the noise distribution of their homes. Their familiarity with the statistical characteristics of this distribution allows them to determine a reasonable criterion for "intrusive" noise events, and is the basis for their ability to decide whether or not a particular noise event is a part of their customary long-term residential noise exposure.

Temporal Assumptions

Another important set of assumptions concerns temporal characteristics (starting time and duration) of the decision epoch. For simplicity, it is assumed that the starting time and duration of the decision epoch is identical to that of the intruding noises. Thus, the duration of the decision epoch might be a fraction of a second in the case of impulsive noises, such as sonic booms, or tens of seconds in the case of aircraft flyovers. The duration of the decision epoch might arguably be even longer, on a scale appropriate to making up one's mind whether an entire cycle of noise exposure (say, daily traffic patterns or a few days' worth of construction noise) is part of the local component of the ambient noise environment of one's neighborhood. It is further assumed that the detectability of the noise events is based on some integrated measure of the event's duration.

People integrate energy perfectly over only a limited range of durations (Horonjeff, Fidell, Teffeteller and Green, 1981) when making detection decisions. "Perfect" integration in this sense means that for every doubling in duration, the detectability of a signal increases by 3 dB. For operations greater than about a quarter of a second, people do not integrate the energy in a signal as efficiently as an ideal energy detector, but rather at a rate of about 1.5 dB per doubling of duration.

In the case of annoyance decisions, however, people seem to be able to integrate signal energy over a wider range of durations. Fidell, Pearsons, Grignetti and Green (1970), for example, and later Pearsons and Bennett (1971) have produced data showing essentially perfect integration of energy from 10 ms to 100 s. These results for annoyance studies suggest that

integration for the proposed model should cover a range of durations extending at least to 2 min. However, later tests will be necessary to confirm this assumption.

Another temporal aspect of intruding noises of concern is onset time. Plotkin, Sutherland and Molino (1987) assert that noises with fast onset times, such as those associated with high speed, low altitude flyovers are more annoying than noises with slower onset times (5 - 10 seconds or more).

Frequency Weighting

The general form of equations for estimating the contribution of acoustic information in different spectral regions to detectability of noise intrusions (and hence, the acoustically controlled aspects of annoyance) is well understood (cf. Green and Swets, 1966). Equations specifically applicable to the sort of broadband signals common in community noise settings have been empirically verified (cf. Fidell et al., 1979). There are computer programs and graphic methods (cf. Horonjeff and Fidell, 1982) are available to perform detectability calculations for such signals.

It is not our intent to suggest that audibility calculations be substituted in all cases for simpler metrics of intruding noise levels, such as A-level. This is not necessary, because for any specified combination of background and intruding noise spectra, audibility and A-level differ only by a constant. The calculation of detectability must be performed once only to establish the value of the constant for any set of conditions. Approximate methods could also be developed to simplify even this calculation.

4.2.2.2 General Assumptions About Nonacoustic Variables

Affective State

One of the first difficulties encountered in quantifying the contributions of nonacoustic variables to annoyance judgments is that numeric representations of affective state are arbitrary. There is room for reasonable differences of opinion about the precision and usefulness of techniques for measuring moods, emotions and attitudes. Fortunately, demonstrations of the influences of affective state on annoyance judgments need not await agreement on standard procedures for subjective measurements of affective state.

The problem of arbitrariness can be minimized 1) by using operational definitions for different affective states in any empirical studies intended to validate the model, and 2) by confining quantitative predictions (of the influence of affective states on annoyance judgments) to controllable conditions.

Thus, for example, one might define an unfavorable affective state for experimental purposes as one assumed to exist following some amount of participation in a boring or frustrating task. A favorable affective state could be operationally defined in an experimental context as one assumed to exist following a comparable amount of participation in an interesting and rewarding task. Quantitative treatments of affective states then require nothing more than a few working assumptions, as discussed below.

Concentration on Ongoing Activity

A similar set of issues concerns the arbitrariness of quantifying the sensitivity to noise while concentrating on some activity. As with any affective state, the importance of any measure of task susceptibility to disturbance by noise intrusion can be debated endlessly.

People may be easily distracted from tasks requiring little mental effort, because the meager attentional demands of such tasks leave people with ample resources for attending to extraneous (nontask related) stimulation. Even though people engaged in simple tasks may be very aware of noise intrusions, the performance consequences of this awareness are often slight. Does the noise of an aircraft overflight interfere with walking the dog or weeding the garden? Even if it did, would it matter very much whether it took an extra ten seconds to walk the dog or to pull a weed?

Likewise, people performing tasks which require intense concentration may not be easily disturbed by noise intrusions, simply because they have little or no spare capacity for attending to noise intrusions. However, even though people performing complicated tasks may be only dimly aware of noise intrusions, the consequences of interfering with complex task performance could be disastrous. Might not a noise intrusion be the last straw that spoils a diamond cutter's aim or breaks a brain surgeon's concentration?

A further complication is that, depending on an individual's training and skill the same task may require considerable attention from one person but little attention for another. The same task can also be difficult at one time but simple at another for the same individual. Thus, the same noise that interferes with a beginning typist's hunt for keys may have no effect at all on a skilled typist's effortless performance.

Most of these conceptual difficulties may once again be avoided by adopting simple operational definitions of sensitivity to disturbance and by restricting predictions to conditions amenable to empirical manipulation. It is not necessary to make fine distinctions between the sensitivity of brain surgeons and diamond cutters to disturbance by noise if one's purpose is merely to establish the principle that concentration on tasks affects tolerance for noise intrusions.

Costs and Payoffs

The issues involved in quantifying costs and payoffs of decision outcomes are similar to those discussed above. Costs and payoffs for annoyance decisions are not exclusively monetary, may vary over time, and may be either situation- or source-specific. The simplest way to these issues is to demonstrate that costs and payoffs can in fact influence annoyance decisions under controlled conditions. Consider an experimental situation in which people engaged in a profitable piecework task can obtain relief from distracting noise intrusions by stopping what they are doing long enough to report the annoying noise exposure. If the experimental situation is arranged so that people lose more money by taking the time necessary to report annoyance than they can gain from making the report, it is likely that they will report annoyance less often than under a complementary set of costs and payoffs. The entire issue may be moot, however, if one's concern is only for the effects of high level noise intrusion (cf. Appendix D).

4.3 Sample Calculations

One way to make the discussions in the earlier portion of this chapter more concrete is to work through a few cases based on convenient working assumptions. The following assumptions are made primarily for clarity. Variants of the assumptions may be more appropriate to particular circumstances, and may be adopted without loss of theoretical generality.

Working Assumption 1: Affective states and the sensitivity of ongoing activity to noise interference are independent random variables with approximately Gaussian distributions. The units used to express these variables are decibels of equivalent signal level (v.i.).

Working Assumption 2: The total range over which annoyance judgments are influence by the degree of concentration on an ongoing activity is equivalent to 10 dB. This estimate is based on a comparison of the data of Fidell and Teffeteller (1981) (presented earlier in summary form in Figure 3-1) and that of Pearsons, Fidell, Horonjeff and Teffeteller (1979).

Subjects in both of these studies were asked to press a button when they first noticed an intruding noise. Those in the experiment of Pearsons et al. were not preoccupied by any foreground task, while those in the study of Fidell and Teffeteller were engaged in an absorbing foreground task. Signal levels first noticed by subjects busy with a foreground task were much

higher than those noticed by subjects not engaged in a foreground task. The average difference in detectability of intruding sounds when first noticed in the two studies was roughly 10 dB.

Working Assumption 3: A comparable range of effect is assumed for the influence of affective state on annoyance judgments in the absence of any other quantitative information.

Working Assumption 4: The tolerance index is formed by taking the product (logarithmic sum) of the numerical values of these two independent random variables. Implying a simple compensatory relationship between affective state and concentration on ongoing activity in determining the value of the tolerance index.

Working Assumption 5: The ratio of payoffs to costs and the *a priori* odds ratio may also be expressed in decibel-like (10*log) units. However, since the effects of these two variables are small except under low signal to noise ratio conditions (cf. Appendix D), they are not considered in the example discussed below.

Working Assumption 6: The value of the decision criterion therefore reduces to the value of the tolerance index.

Table 4-1 illustrates the interactions of the variables described above as applied to the data of Fidell and Teffeteller (1981) shown in Figure 3-1. *It should be remembered that the attention* of the subjects in those tests was focused on an absorbing task. The spreadsheet header shows the combinations of values selected for the model's three independent variables for a nominal case. These variables are the signal duration, the observer's affective state, and the observer's concentration on ongoing activity at the time a noise intrusion occurred.

The nominal values shown in Table 4-1 are expressed in linear or logarithmic units. Duration, for example, is specified in seconds, but is converted internally in the spreadsheet into decibel-like (10*log) form to calculate the integrated detectability of a noise intrusion in d'-seconds. Affective state and concentration on activity are both in decibel-like units, so that their product, the tolerance index, can be treated in the spreadsheet header as the sum of these two quantities.

The top row of the spreadsheet lists a range of A-weighted sound pressure levels of noise intrusions. These figures correspond to the integrated detectability figures immediately below them. For the particular set of intruding noises and background distribution of the experiment of Fidell and Teffeteller, the two sets of figures differ only by a constant (33 dB).

The next five rows list decisions for increasing intensities of annoyance associated with noise intrusions of increasing level. These decisions result from application of the decision criterion calculated for the set of conditions noted on the spreadsheet header. Thus, under the

Table 4-1: Spreadsheet Demonstrating Calculation of the Annoyance of Individual Noise Intrusions for Specified Conditions

AFFECTIVE STATE: 0 (NEITHER FAVORABLE NOR UNFAVORABLE) RESULTING TOLERABILITY INDEX: 5 [illegible] OF NOISE INTRUSIONS [illegible] 1 RATIO OF BENEFITS TO COSTS (1:1) OF DECISION OUTCOMES: 1 RESULTING 10 LOG (DECISION CRITERION): 0

CONCENTRATION ON ONGOING ACTIVITY: 0 (NEITHER FOCUSED ON TASKS NOR FOCUSED ON DISTURBANCE)

SPL OF INTRUDING NOISE IN DB(A)

	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65
10 LOG (N*T)	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
NOT AT ALL ANNOYED	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
MODERATELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES
VERY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
HIGHLY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
10 LOG (N*T)	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
NOT AT ALL ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
MODERATELY ANNOYED	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
VERY ANNOYED	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
HIGHLY ANNOYED	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

nominal conditions represented in Table 4-1, noise intrusions with levels less than 50 dB(A) (10 log d'-seconds less than 17) are predicted to be not at all annoying. Noise intrusions with A-levels between 50 and 60 dB(A) are considered slightly annoying; those with levels between 61 and 68 dB(A) are moderately annoying; and so forth.

An illustration of the effect of the tolerance index on the probability of annoyance is shown in Figure 4-2.

Notice that at a certain intrusion level (10 log d' = 40) and a high tolerance index of 15, the probability of being extremely annoyed is only 0.02. However, at the same level but with a low tolerance index of -5 the probability of being extremely annoyed is about 0.70. Another illustration of the effect of the tolerance index is shown in Figure 4-3. The figure shows that for noises with an intrusion level of 30 (10 log d' = 30) people with a tolerance index of 15 judge them to be only slightly annoying. On the other hand people with a tolerance index of -5 would judge the same sounds to be very annoying.

Appendix E contains a set of spreadsheets and figures that illustrate the effects of other combinations of model parameters on the predicted annoyance of noise intrusions of varying level. As may be seen from these spreadsheets, variations in the tolerance index over a range of 20 dB (100:1) change the level at which a noise intrusion is considered annoying by an equivalent amount. Thus, for example, an observer who, under nominal conditions would find a noise intrusion of 60 dB(A) moderately annoying, would find the same noise intrusion moderately annoying at a level of only 50 dB when his tolerance for noise intrusions was 10 dB lower than nominal. The same noise intrusion would not be judged moderately annoying until it reached a level of 70 dB when the observer's tolerance was 10 dB higher than nominal.

4.4 Providing Theoretically Based Answers to Annoyance Questions

One of the benefits of the theoretical framework developed above is that it makes it possible to suggest systematic answers to the questions raised in Section 3.2, as noted below.

- Why are some sounds annoying to some people, but not to others?

  A decision to treat an intruding sound as annoying depends primarily upon: 1) its relationship to the reference noise distribution; 2) a person's momentary affective state; and 3) a person's concentration on activity at the time the noise intrusion occurred. People also consider the *a priori* probability that a noise intrusion will occur, and the costs and payoffs of annoyance decisions for low level noise intrusions. Because different members of a community may compare noise intrusions with different reference noise distributions, or may be in different affective states, or may be engaged in different activities at the time of occurrence of

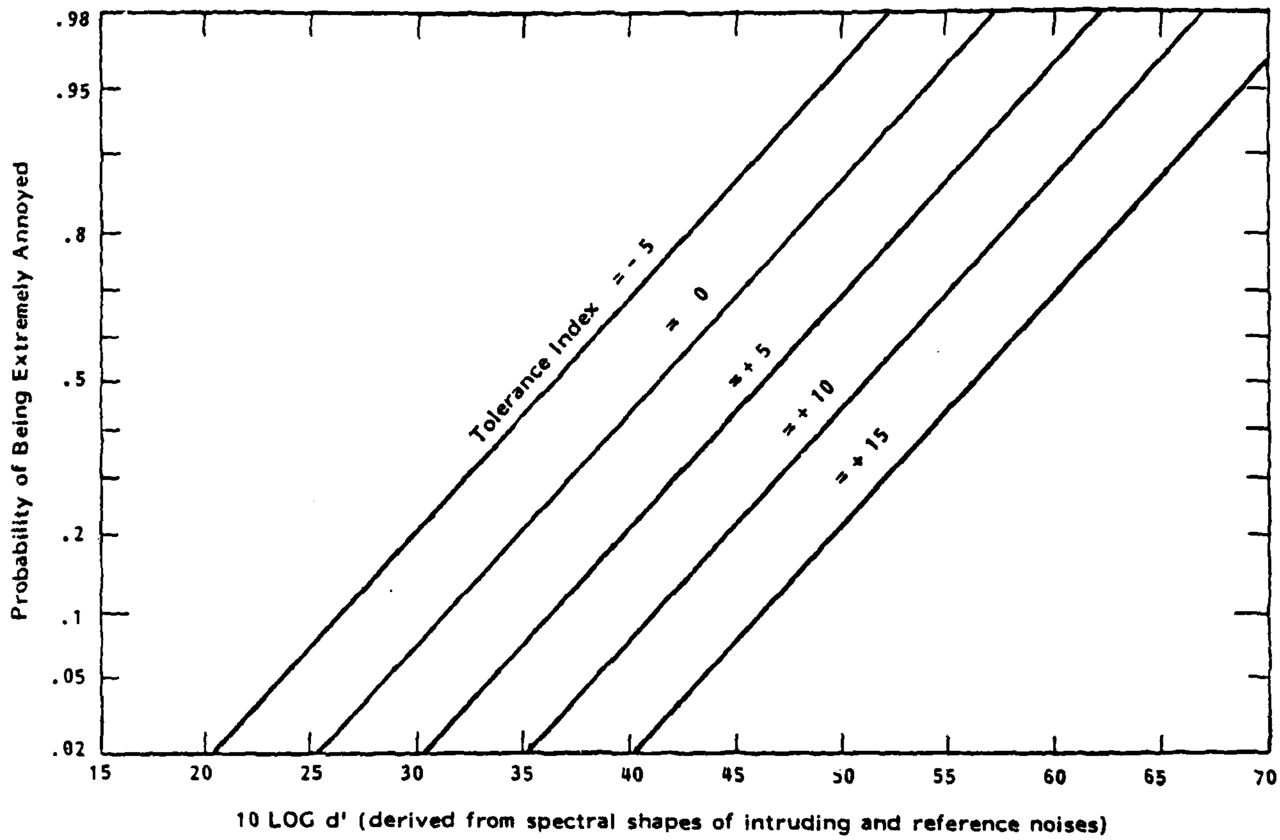

Figure 4-2: Effect of Tolerance Index on Probability of Annoyance

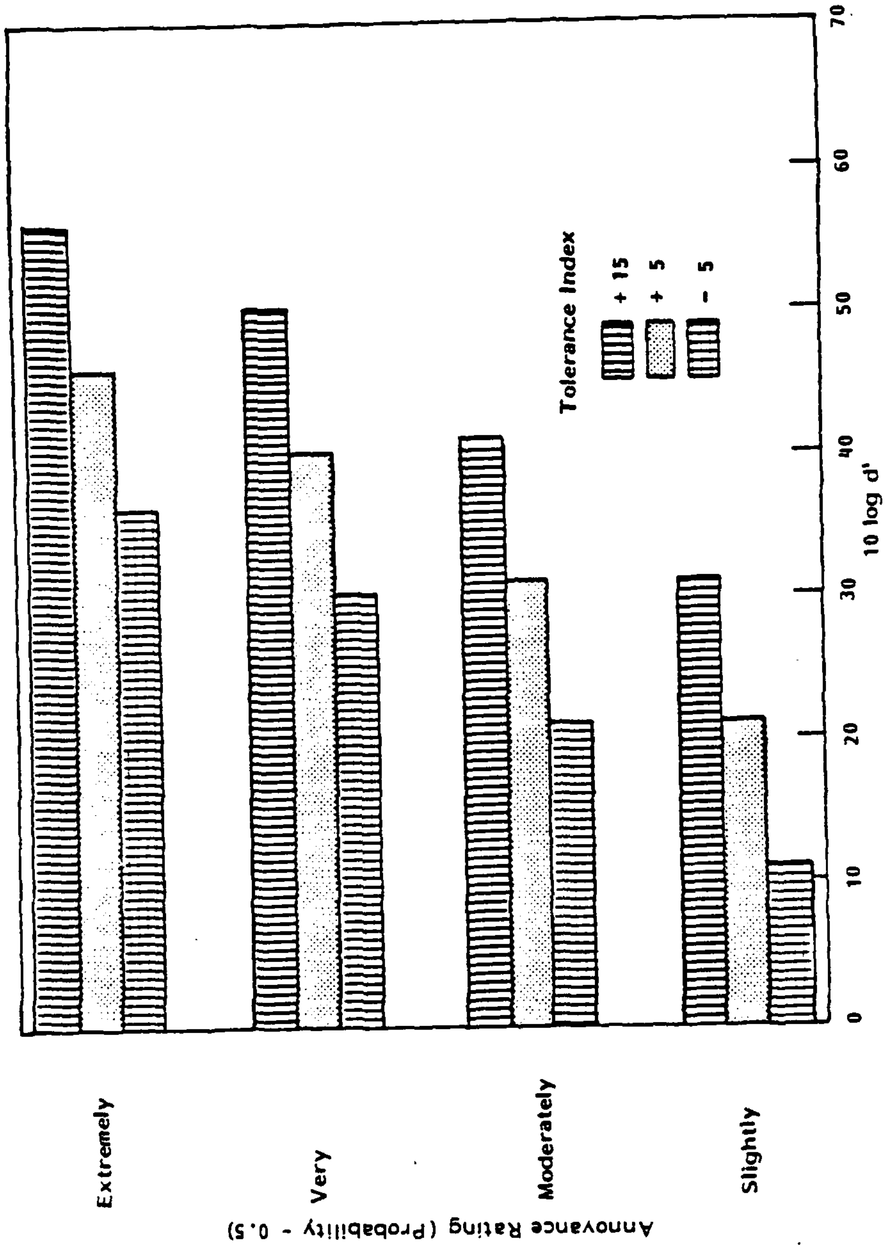

Figure 4-3: Effect of Tolerance Index on Judged Annoyance of Individual Noise Intrusions

noise intrusion, it would be surprising if all people in a residential setting always agreed on the annoyance of intruding noises.

- Why is the same magnitude of sounds annoying to people at some times but not at others?

  A decision to consider an intruding sound as annoying depends on the above-mentioned factors, whose temporal variability is completely unrelated to the time noises occur from diverse sources. Furthermore, it is the relative level of noise intrusions with respect to background noise distributions that is the primary acoustic determinant of annoyance, not their absolute sound pressure levels. The same noise intrusion occurring in different noise backgrounds should be differentially annoying.

  In short, annoyance decision making is a fundamentally probabilistic process. It is unlikely that a deterministic approach that assigns a fixed annoyance to a noise intrusion of a fixed level can yield useful predictions of the annoyance of noise intrusions outside the laboratory.

- What are the relative contributions of acoustic and nonacoustic factors to annoyance?

  Acoustic factors such as signal-to-noise ratio, rise time, and duration jointly determine the integrated detectability of noise intrusions. Nonacoustic factors combine to establish the value of integrated detectability that is considered annoying under any particular set of conditions. The acoustic properties of intruding noises are therefore necessary but are insufficient determinants of annoyance.

- What are the dynamics (i.e., the time constants of onset and decay) of annoyance?

  The amount of time it takes for long term community response to shift after a sudden change in noise exposure level due to such situations as the opening of a new airport or the closing of a runway is uncertain at this time. Estimates based on the limited data described in Section 2.3 suggest time constants ranging from 25 to 1,600 days. Although the response time effect could be incorporated into the model, the limited data currently available does not warrant it at this time.

- Is annoyance something other than duration-corrected loudness?

  Loudness is a sensation lacking any significant cognitive component that can be predicted on the basis of deterministic procedures. Annoyance is an attitude whose acoustic determinants include factors that do not directly affect loudness. Annoyance is also affected by nonacoustic factors which have little, if any, effect on loudness judgments.

- Can publicity affect the annoyance of noise exposure?

  Publicity can affect annoyance to the extent that it can convince people that the appropriate reference distribution for making annoyance judgments is one that includes particular noise sources. Publicity may also affect the costs and payoffs associated with annoyance decisions, but the costs and payoffs of annoyance decisions have only a limited influence on the annoyance of high level noise intrusions.

- Do predictable episodes of noise exposure produce less annoyance than unpredictable episodes of exposure of the same magnitude?

  Predictability of noise exposure can affect its annoyance to the extent that people are willing to consider predictable noise intrusions a part of the reference distribution.

- Does the ambient noise environment in which sounds are heard affect their annoyance?

  The ambient noise distribution can affect the annoyance of intruding noises (especially those whose frequency resemble the ambient noise and which does not greatly exceed its level) by reducing the their audibility. However, ambient noise levels measured at fixed locations, whether indoors or outdoors, may be poor predictors of the momentary ambient noise distribution at the ear. Furthermore, the ambient noise environment that can be conveniently measured may not closely resemble the reference distribution to which people compare intruding noises.

- Do expectations about the appropriateness of noises heard under different circumstances affect the annoyance of noise intrusions?

  People may tolerate exposure to noises which are plausible parts of different reference noise distributions, such as the noises of children in the home, of vehicles on the street, of machinery in the workplace, etc.

- Why does the A-level of a sound serve as a partial predictor of its annoyance?

  The A-weighted sound pressure level of an intruding sound may correlate well with its signal to noise ratio with respect to the reference distribution. When nonacoustic variables (e.g., affective state and concentration on behavior) that also affect annoyance decisions assume nominal or self-canceling values, the correlation between A-level and detectability of intruding noises may suffice to predict annoyance decisions with useful precision.

4.5 Some Limitations of the Model

The working assumptions adopted above are not intended to universally apply to the prediction of noise-induced annoyance in all settings. In particular, alternative assumptions may be needed to adapt the model to nonresidential (i.e., occupational or recreational) situations. Most of the refinements needed to extend the model to nonresidential circumstances of exposure stem from two sources:

1) the model requires a familiar, ever present ambient noise environment and focuses on the effective signal to noise ratios of intruding noises rather than their absolute sound pressure levels; and

2) the model addresses only the immediate linkages between noise exposure and

annoyance, not the second order linkages among noise exposure, one or more intermediate effects (such as sleep or speech interference), and annoyance.

The difficulty in extending the model to nonresidential settings may not be a serious limitation, because the signal to noise ratio and the absolute level of intruding noises are likely to be highly correlated in many circumstances. In environments in which the level of ambient noise distribution is itself very high, however, the relative character of the basic model may be inappropriate.

The difficulty is to deal with very high level noise intrusions, which may invariably awaken or startle people requires elaboration of the model. As noted in Appendix B, however, these situations are not the most common forms of aircraft noise exposure in the United States. The model will of course predict that such very high level noise intrusions will be highly annoying, but it will not account for further annoyance caused by awakening or startle.

5. EMPIRICAL TEST DESIGN FOR MODELS

The two models developed in the previous chapters are internally consistent, relatively simple, and at least superficially plausible. They are unlikely to gain complete acceptance, however, until hypotheses derived from them have been empirically verified under controlled laboratory conditions. They will not be fully useful to the USAF until some experience has been gained in applying them to field settings that will permit fine tuning of their assumptions. This chapter suggests two types of empirical studies useful for these purposes.

5.1 Laboratory Studies of the Individual Noise Intrusion Annoyance Model

Two aspects of this model should receive the highest priority for empirical confirmation: 1) that integrated detectability of a noise intrusion with respect to a reference distribution is, in fact, a reasonable and useful physical basis for reaching annoyance decisions; and 2) that the two nonacoustic factors (affective state and concentration on ongoing activity) which affect the tolerance index, operate as conjectured.

5.1.1 Acoustic Determinants of Annoyance

A conventional annoyance judgment study is adequate to test the former issue. Approximately 30 paid observers can be instructed to judge the relative annoyance of pairs of sounds which vary in duration, frequency and absolute level, and which are heard in the presence of at least two ambient noise environments. An adaptive experimental design such as the Parameter Estimation by Sequential Testing (PEST) (Taylor and Creelman, 1967) can be used to efficiently establish the indifference point for each such pair of sounds.

One sound of fixed level and duration would not vary throughout a determination of relative annoyance, while the other could vary in level and duration. The two sounds would be randomly presented, and closely spaced in a two observation interval, forced choice trial procedure. Subjects would have a well defined response interval immediately following each presentation of a pair of sounds in which to indicate the more annoying sound. Only about 30 presentations of each signal pair should be needed to reach the point of subjective equality of annoyance (the point at which the subject cannot reliably distinguish the annoyance of one signal from the annoyance of the other) with a standard error between one to two dB.

All judgments of given signal pairs would be made within a single experimental session

lasting about two hours. Subjects would be trained during one or more preliminary sessions to familiarize them with trial procedures. They would have to demonstrate their understanding of the instructions by reaching a level of training criterion in which their comparisons of the annoyance of one or more signals versus themselves (as opposed to a comparison of one signal versus another) produced a negligibly small difference in level or duration. A certain proportion of the comparisons made in each test session would be reserved for test/re-test reliability measurements. Every effort would be made over test sessions to hold the external conditions constant that might affect the subject's affective state and concentration.

Annoyance judgments would be made in the presence of at least two reference noise distributions that differ sufficiently in frequency as to differentially mask a set of test signals. A set of approximately twelve aircraft flyovers and other environmental noises would be selected to produce a ten- to twenty-dB range of integrated detectabilities across the background noise conditions. A certain proportion of judgments could also be repeated at different absolute levels (varying signal level while keeping background level constant, and varying both signal and background noise level).

Equipment calibration, signal production, and data collection would be computer controlled. Automated procedures for documentation would also be developed so that experimental results would be preserved in computer-compatible formats from collection through analysis and archiving.

A study as described above would be capable of yielding definitive answers to two hypotheses:

Hypothesis 1 - The annoyance of noise intrusions is determined by their relative levels with respect to ambient noise environments, rather than by their absolute levels.

Hypothesis 2 - The duration and detectability of intruding noises are interchangeable on an equal energy basis for determining annoyance.

5.1.2 Nonacoustic Determinants of Annoyance

5.1.2.1 The Influence Which Affective State Has on Annoyance Judgments

The purpose of this study would be to demonstrate the degree to which test subjects' affective states can affect category scale judgments in the annoyance of noise intrusions. The strategy would be to operationally define two very different affective states and compare annoyance judgments for the same signals made under each. For example, an unfavorable affective state might be defined as that resulting from a half hour's participation in a difficult and

fruitless task, while a favorable affective state might be defined as that resulting from a half hour's participation in an interesting and rewarding task.

One example of a difficult and fruitless task is attempting to solve sets of complex maze problems for a piece rate incentive. Each maze would be generated and displayed by a computer. Subjects would have to trace through the maze using a cursor. Mazes could be generated in varying degrees of complexity, including multiple blind alleys, multiple entry points, and multiple routes to the goal box. The goal box would display a monetary reward that would be paid upon reaching it.

A set of problems intended to frustrate subjects would include a high proportion of several payoffs but insoluble problems, at which test subjects would have to waste a considerable time and mental effort before it could be determined that the current maze was, in fact, insoluble. A set of problems intended to please subjects would include a high proportion of soluble mazes of similar complexity, at which the subjects could readily earn appreciable bonuses.

At various intervals during the maze-solving, subjects would be asked to judge the annoyance of a set of sounds. If the role assigned affective state in establishing the tolerance index in the annoyance model of individual noise intrusions is correct, then sounds heard while the test subjects are in an unfavorable affective state should be reported as more annoying than the same sounds heard while the test subjects are in a favorable affective state.

Another example of a foreground activity is a proofreading task in which test subjects search for target characters embedded in distracting characters on a computer-generated display. Such a task provides ample opportunities for varying difficulty and interest levels.

5.1.2.2 The Influence Which Concentration on Activity Has on Annoyance Judgments

A similar experiment could demonstrate the effect which concentration on activity has on annoyance judgments. A task would be devised which could systematically vary concentration, but which would always produce similar payoffs per unit time. This task would arguably leave affective state unchanged while varying concentration. An example of such a task might be a video game requiring different degrees of eye hand coordination, played for stakes that compensated difficulty with payoffs. Although the concentration required to play the game could vary greatly between experimental sessions, the payoffs would remain fairly constant.

At intervals throughout the experimental session subjects would be asked to judge the annoyance of a set of aircraft flyovers and other sounds. If the role assigned to concentration on activity in establishing the tolerance index for the annoyance model of individual noise intrusions is correct, then sounds heard while subjects are concentrating most deeply on the task should be judged less annoying than sounds heard while the subjects are only slightly involved in the task.

5.1.2.3 The Influences of Costs and Payoffs on Annoyance Judgments

It is not clear what can be learned from a study in which people are paid to make annoyance judgments of varying intensities. If their annoyance judgments closely track costs and payoffs, it can at most be argued that they were able to follow instructions and that their responses could be purchased. If their annoyance judgments do not closely track the costs and payoffs, it would be difficult to argue that the experimental findings are applicable to realistic settings, for lack of either credible incentives or face validity.

Realistically, costs and payoffs for annoyance decisions are not usually limited to monetary ones. Noise exposure is only one of many environmental factors that affect people's satisfaction within their living conditions. Furthermore, the role assigned to costs and payoffs in the annoyance model for noise intrusion is minor in the case of high signal-to-noise ratio sound intrusions (e.g., aircraft noise). Verification of the effect of costs and payoffs on annoyance decisions is therefore not now a high priority concern.

5.2 Field Tests

Attempts to verify the model of community annoyance developed in Chapter 2 are complicated by the difficulty of controlling the factors that affect the response criterion variable (K) outside the laboratory. It is unclear whether communities exposed to aircraft noise can be found in which the USAF can intervene in a worthwhile manner to change K values. Ethical considerations and potential controversy associated with such interventions also require careful examination.

The alternative a directly manipulating K is a case study approach, which various sub-populations might be identified and in which there would be a reasonable *a priori* basis for expecting differences in K values. Perhaps the most obvious example of a sub-population that might be expected to have a different K value from that of the general population is the set of people who earn their livings from aviation-related activities. Another sub-population of interest might be members of aircraft noise protest groups. Yet others might be identified on the basis of their responses to questionnaires concerning attitudes toward issues other than aircraft noise exposure.

A case study like this would identify sub-populations with common attitudes that could be expected to be reflected in their overall willingness to report a consequential degree of annoyance to aircraft noise exposure. Separate dosage-effect relationships could be constructed empirically for each such identifiable sub-population. The amount of K change necessary to fit

each of these dosage-effect relationships could then be determined, and used as guidelines for predicting the prevalence of annoyance in similar sub-populations elsewhere.

References

American National Standards (ANSI). "Sound Level Descriptors for Determination of Compatible Land Use", ANSI S3.23, 1980

Bishop, D.E., (1973). Program for the Measurement of Environmental Noise. Report No. DOT-TST-74-4. Washington, D.C.: U.S. Department of Transportation, Office of Noise Abatement. (See particularly Appendix A.)

Borsky, P.N., (1973). A New Field-Laboratory Methodology for Assessing Human Response to Noise. NASA CR 2221, National Aeronautics and Space Administration.

Cavanaugh, W.J., Farrell, W.R., Hirtle, P.W., Watters, B.G. (1962). "Speech privacy in buildings". Journal of the Acoustical Society of America, 34, 475.

Cermak, G.W. (1979). "Exploratory laboratory studies of the relative aversiveness of traffic sounds". Journal of the Acoustical Society of America, 65, 112-123.

Committee on Hearing, Bioacoustics and Biomechanics Assembly of Behavioral and Social Sciences (CHABA). (1977). Guidelines for Preparing Environmental Impact Statements on Noise. Washington D.C.: National Research Council.

Eldred, K. McK. (1971). Community Noise, Report No. NTID300.3. Washington D.C.: U. S. Environmental Protection Agency, Office of Noise Abatement and Control.

Fidell, S. (1984). "Community Response to Noise". In D. Jones & A. Chapman (Eds.), Noise and Society. Chichester: John Wiley and Sons.

Fidell, S., & Horonjeff, R. (1982). "A Graphic Method for Predicting Audibility of Noise Sources".

Fidell, S., & Teffeteller, S. (1981). "Scaling the Annoyance of Intrusive Sounds". Journal of Sound and Vibration, 78(2), 291-298.

Fidell, S., Horonjeff, R., & Green, D.M. (1981). "Statistical analyses of urban noise". Noise Control Engineering, 16(2), 75-80.

Fidell, S., Horonjeff, R., Mills, J., Baldwin, E., Teffeteller, S., & Pearsons, K. (1985). "Aircraft noise annoyance at three joint air carrier and general aviation airports". Journal of the Acoustical Society of America, 77(3), 1054-1068.

Fidell, S., Teffeteller, S., Horonjeff, R., & Green, D.M. (1979). "Predicting annoyance from detectability of low level sounds". Journal of the Acoustical Society of America, 66(5), 1427-1434.

Fidell, S., Pearsons, K., Grignetti, M., & Green, D. (1970). "The Noisiness of Impulsive Sounds". Journal of the Acoustical Society of America, 48, 1304.

Fletcher, H. (1938). "Loudness, masking and their relation to the hearing process and the problem of noise measurement". Journal of the Acoustical Society of America, 9, 275-293.

Fletcher, H., A. H. Beyer & A. B. Duel. (1930). Noise Measurement in City Noise. Report of the Noise Abatement Commission, Department of Health, City of New York.

Fletcher, H., & W. A. Munson. (1933). "Loudness, its definition, measurement and calculation". Journal of the Acoustical Society of America, 5(82), 808.

Galloway, W.J. (1984). Assessment of Community Response to High- Energy Impulsive Sounds. Report of Working Group 84, Committee on Hearing, Bioacoustics, and Biomechanics. Washington D.C.: National Research Council, National Academy of Sciences.

Galloway, W. J., & Jones, G. (1971). Motor Vehicle Noise: Identification and Analysis of Situations Contributing to Annoyance. Paper #720276, Report No. 2082, Bolt Beranek and Newman Inc., to Automobile Manufacturers Association.

Galloway, W. J. (1974). Community Noise Exposure Resulting from Aircraft Operations: Technical Review. Report AMRL)TR-73-106, Bolt Beranek and Newman.

Galloway, W. J., Eldred, K. McK., & Simpson, M. A. Population Distribution of the United States as a Function of Outdoor Noise Level, (The "100-Site Study"). Report No. 2592, Bolt Beranek and Newman Inc., to U. S. Environmental Protection Agency, Office of Noise Abatement and Control, Washington, D. C.

Galt, R. H. (1930). "Results of Noise Surveys, Part I: Noise out of doors". Journal of the Acoustical Society of America, 2(30), 58.

Gjestland, T. (1987). "Assessment of annoyance from road traffic noise". Journal of Sound and Vibration, 112(2), 369-375.

Gjestland, T. & Oftedal, G. (1980). "Assessment of noise annoyance: the introduction of a threshold level in L_{eq} calculations". Journal of Sound and Vibration, 69, 603-610.

Green, D.M., & Swets, J.A. (1966). Signal Detection Theory and Psychophysics. New York: John Wiley and Sons.

Horonjeff, R., Fidell, S., Teffeteller, S., & Green, D.M. (1982). "Behavioral awakening as functions of duration and detectability of noise intrusions in the home". Journal of Sound and Vibration, 84(2).

HUD (U. S. Department of Housing and Urban Development). (8/4/71, amended 9/1/72). Noise Abatement and Control: Departmental Policy, Implementation Responsibilities and Standards. Departmental Circular 1390.2.

International Organization for Standardization (ISO). (1971). Noise Assessment with Respect to Community Response. International Recommendation 1996. Geneva.

Johnston, G. & Haasz, A. (1979). "Traffic background level and signal duration effects on aircraft noise judgment". Journal of Sound and Vibration 63 (4), 543-560.

Kryter, K. D. (1982). Rebuttal by Karl D. Kryter to Comments by T.J. Schultz. Journal of the Acoustical Society of America, 72(4), 1253.

Kryter, K.D, & Pearsons, K.S. (1963). "Some effects of spectral content and duration on perceived noise level". Journal of the Acoustical Society of America, 35(6), 866-883.

Kryter, K. D. (1982a). "Community annoyance from aircraft and ground vehicle noise". Journal of the Acoustical Society of America, 72, 1222-1242.

Molino, J.A. (1974). "Measuring human aversion to sound without verbal descriptors". Perception and Psychophysics, 16, 303-308.

Pearsons, K.S., Fidell, S., Horonjeff, R., & Teffeteller, S., (1979). Noticeability and Annoyance of Electrical Power Transformers in Urban Noise Backgrounds. BBN Report 4004.

Pearsons, K. S., & Bennett, R. (1974). Handbook of Noise Ratings. Report No. NASA CR-2376. Washington D.C.: National Aeronautics and Space Administration.

Pearsons, K.S., & Bennett, R. (1971). "Effects of Temporal and Spectral Combinations on the Judged Noisiness of Aircraft Sounds". Journal of the Acoustical Society of America, 49,(4), 1076-1082.

Plotkin, K.J., Sutherland, L., & Molino, J. (1987). Environmental Noise Assessments for Military Aircraft Training Routes, Vol. 2, Recommended Noise Metrics, AAMRL-TR-87-001.

Preis, A. (1987). Intrusive Sounds. Applied Acoustics, 20, 101-127.

Raiffa H., & Schlaifer R. Applied Statistical Decision Theory. Boston: Harvard University, Graduate School of Business Administration, Division of Research.

Rice, C.G. (1977). "Investigation of the Trade-Off Effects of Aircraft Noise and Number". The Journal of Sound and Vibration, 522,(3), 325-344.

Schultz, T. J. (1972). Community Noise Ratings. London: Applied Science Publishers Ltd.

Schultz, T. J. (1973). "Instrumentation for Community Noise Surveys". Proceedings of Inter-Noise 73, Copenhagen, 22-24. Paper G23X15.

Schultz. T. J. (1979). "Community Annoyance with Transportation Noise". In R. J. Peppin and W. Rodman (Eds.), Community Noise Symposium, ASTM STP 692, American Society for Testing and Materials, 87-107.

Schultz, T. J. (1982). Community Noise Rating (2nd ed.). New York: Applied Science Publishers.

Schultz, T. J. (1982a), Comments on K. D. Kryter's paper, "Community annoyance from aircraft and ground vehicle noise". Journal of the Acoustical Society of America, 72(4), 1243-1252.

Schultz, T. J. (1978). "Synthesis of social surveys on noise annoyance". Journal of the Acoustical Society of America, 64(2), 377-405.

"Sozio-psychologische Fluglarmuntersuchung in Gebiet der drei Schweizer Flughafen: Zurich, Genf, Basel". (Socio-psychological Investigation of Aircraft Noise in the Vicinities of Three Swiss Airports: Zurich, Geneva, Basel].) no report number, Arbeitsgemeinschaft fur soziopsychologische Fluglarmuntersuchungen, (Bern, June 1973).

Swets, J. A. (1964). Signal Detection and Recognition by Human Observers.

Tatge, R. B. (1975). "Effect of community population on applicability of noise rating procedures". Noise Control Engineering, 4, 65-70.

Taylor, M. M. & Creelman, C. D. "PEST: Efficient Estimates on Probability Functions". Journal of the Acoustical Society of America, 41, 782-787.

Tracor, Inc. (1971). Community Reaction to Airport Noise. Vol. 1: NASA CR 11761; Vol. II: NASA CR 111316.

Wegel R. & Lane, C. (1924). "The Auditory Masking of One Pure Tone by Another and its Probable Relation to the Dynamics of the Inner Ear". Physical Review, 23(2), 266-285.

Wright, W. D. (1967). The Rays are not Colored. New York: American Elsevier.

Young, R. W. (1965). "Revision of the speech-privacy calculation". Journal of the Acoustical Society of America, 38, 534.

Zwislocki, J. J. (1969). "Temporal Summation of Loudness: An Analysis". Journal of the Acoustical Society of America, 46, 431-441.

Appendix A
Derivation of Empirical Dosage-Effect Relationship for Annoyance

A.1 The Origins of Regulatory Reliance on Dosage-Effect Relationships

The introduction of jet transport aircraft into service in the late 1950's provided the impetus for much of the present concern with environmental noise. As various agencies became concerned with environmental noise effects in the early 1960's, they were concerned first with aircraft and road/street traffic. These two noise sources were singled out for early attention because (a) they were conspicuous contributors to the urban noise climate, and (b) there was money available to apply to the problem.

Early research on transportation noise effects was simplistic. The only major concern was "how much noise is too much?" and the answers came in as many varieties as there were noise studies. Researchers in different countries were isolated from each other, and each country was concerned only with its most salient (for the moment) problem. There was little communication between researchers and no coordination of research efforts.

In this state of technical innocence, the U. S. Department of Housing and Urban Development (HUD) adopted the first federal policy on noise abatement and control sufficiently sweeping to affect the outdoor noise environment nationwide (HUD, 1971). HUD's policy was intended, among other things, "to foster the creation of controls and standards for community noise abatement..."; but HUD would not support planning or construction for dwelling units on sites that had, or were projected to have, unacceptable noise exposures.

HUD's standards of unacceptable noise were stated in peculiar terms, even in an era when few standards had been accepted. They bore little relation to the metrics of noise exposure that had been used in the few social surveys up to that time (in England, Austria, France, The Netherlands and the USA). In fact, HUD's standards for all community noises except that of aircraft were adapted from the then current OSHA limits on occupational noise exposure established for the hearing protection of industrial workers. Only at the insistence of noise experts around the country were HUD's original limits gradually reduced from the range relevant to hearing damage to a range appropriate to residential environments.

HUD's non-aircraft noise standards were even framed in a format similar to OSHA's: the site noise was judged "Clearly Unacceptable" if the level "exceeds 80 dB(A) 60 minutes per 24 hours," or "exceeds 75 dB(A) 8 hours per 24 hours," etc. No dwellings would be supported by

HUD at such sites, even if the dwellings were provided with special noise attenuation measures. Only a few urban sites would be expected to have noise levels this high.

A site was judged "Normally Unacceptable" if the site noise level "exceeds 65 dB(A) 8 hours per 24 hours." This is the part of the noise standard that usually determined whether or not HUD assistance would be granted. HUD approval of such sites for dwelling construction would be given only if special noise attenuation measures were provided in the building plans.

Unfortunately, there were no instruments available that could measure the noise exposure at a proposed building site in HUD's new terminology. Thus, it was necessary for the Technical Background to HUD's Noise Guidelines to provide some "interpretation". Equipment was becoming available in the early 1970's that could measure percentile sound levels with reasonable flexibility. The interpretation amounted to finding an equivalence in centile levels (all A-weighted), which represent the percent of the observation period during which the level was exceeded. The centile level that was equivalent to HUD's "Normally Unacceptable" rating was L_{33} = 65 dB(A).

HUD's noise policy was effective and very influential; other U.S. government agencies were encouraged by HUD's policy to further their own noise control efforts. The complete Noise Assessment Guidelines were even translated into German and adopted by the Austrian Department of the Environment.

A.2 Predicting Community Response to Noise

It was soon recognized, however, that any additional progress in noise regulation required a firmer technical footing. In particular, it became evident that a technically based scientific method of inquiring was needed for predicting how communities would respond to noise exposure. Since noise was first recognized as an environmental pollutant, social surveys on noise annoyance have been conducted which attempted to predict the subjective response of the community from an objective measure of some physical characteristic of noise exposure.

Early surveys studied only one particular noise source, for example, aircraft or road traffic. The procedure was to subdivide a neighborhood known to be affected by the noise in question into subneighborhoods, each uniformly exposed to the noise to a different degree. Interviews were then conducted among the inhabitants of the various subneighborhoods to determine whether, and how much, they were annoyed by the noise. In some cases, it was also asked whether the noise interfered with sleep, conversation, listening to the radio or television, etc.

The clear expectation was that such a study would reveal a high correlation between the

degree of noise exposure and the intensity of annoyance felt by neighborhood inhabitants, expressed on an annoyance scale running from a negligible to a considerable amount. Even in the earliest surveys, however, it was found that the correlation between the measured noise exposure and the individual subjective reactions was poor (typically on the order of 0.3 to 0.4). When the responses in a subneighborhood were pooled, the correlation between noise exposure and annoyance responses was much better (but not entirely for substantive reasons), increasing to as much as 0.7 to 0.8. Correlations of this magnitude still leave about half of the variance in annoyance responses unaccounted for by noise alone.

A.3 Synthesis of Social Surveys on Noise Annoyance

It was not until 1978 that a credible synthesis of this body of social survey data emerged, in the form of a dosage-effect relationship published by Schultz (1978). By converting noise exposure metrics to common units and by considering comparable portions of response distributions from disparate annoyance scales, Schultz was able to provide the first view of the forest rather than the trees.

Figure A-1 shows good agreement among the re-interpreted results of a dozen major social surveys. The average of these data (reproduced as Figure 1-1 in the body of this report) was proposed as a reasonable relationship between noise exposure and "community response". The metric of community response was taken to be the prevalence of a consequential degree of annoyance. The original "synthesis" curve was based on eleven surveys; subsequently, four more surveys were published whose results agreed closely with the first synthesis. Adding the new data to the original survey analysis does not change the synthesis curve.

Treating the average curve of Figure 1-1 as a consensus of comparable social surveys, one may still ask how accurately it can predict community response. Figure A-2 shows all the data points from the group of eleven surveys. It also shows two regression curves, one in which all the individual regression curves from the eleven surveys have been given equal weight, and another in which all of the original data points are given equal weight, in order to form a single regression curve. These two regressions are practically identical with one another and with the original average curve.

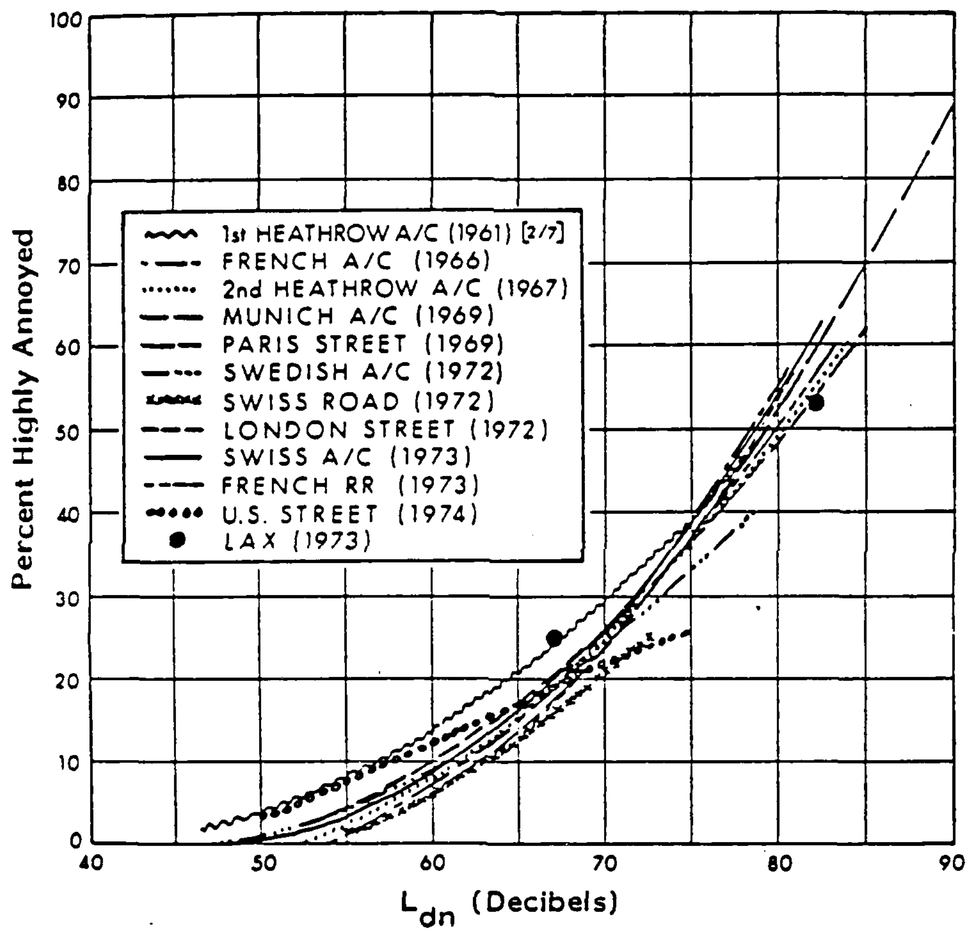

Figure A-1: Summary of Annoyance Data from 11 Surveys that Show Close Agreement and Two Points from Study of Aircraft Noise Annoyance at LAX

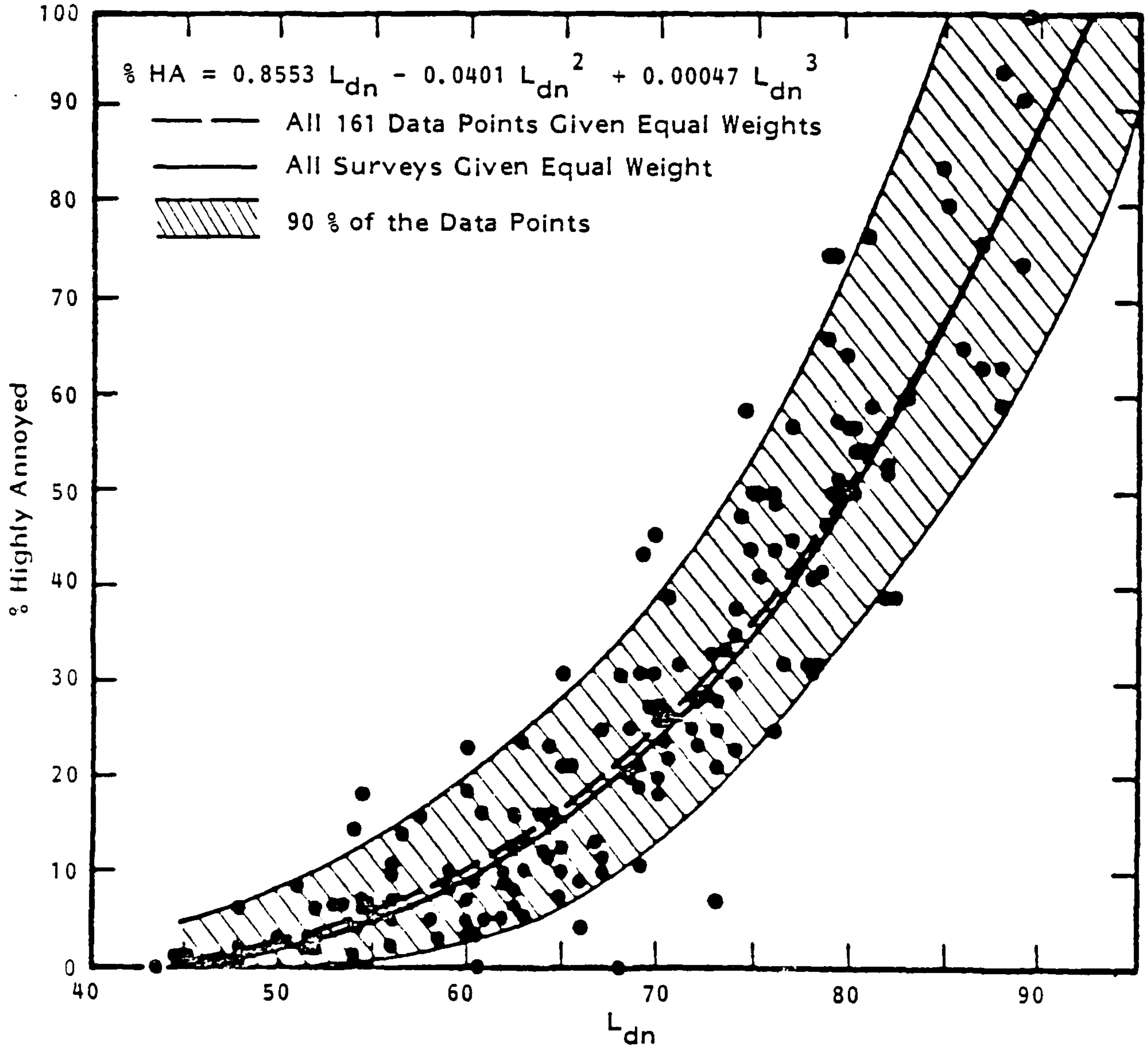

Figure A-2: Summary of All Survey Data Points

A.4 Survey Data Interpretation Uncertainties

Not surprisingly, the appearance of Schultz's "Synthesis" brought forth considerable discussion and criticism. People were quick to point out the hazards of trying to determine who is "highly annoyed" in surveys conducted in different languages using different annoyance scales, and in trying to find a common measure for the noise exposure in surveys where noise exposure was expressed in quite different terms.

It is instructive to trace the major trends in the debate about Schultz's development of a dosage-effect relationship, since an appreciation of this debate underscores the importance of a theoretical basis for any dosage-effect relationship which may be employed by the USAF in its environmental assessments.

A.4.1 Procedures for Counting the "Highly Annoyed" Part of the Population

Of the 18 surveys that Schultz initially studied, 11 of them presented subjective response data in such a way that a highly annoyed fraction could be easily discerned. The definition of "high annoyance" was heavily influenced by the manner in which the Swiss traffic noise and aircraft noise surveys in the early 1970's were reported. In those surveys, people were reported as highly annoyed who responded in the top three out of eleven categories on the response rating scale, that is, in the top 27% of the rating scale.

Although arbitrary, this seemed a reasonable definition of high annoyance, and in any case the reports did not offer any other choice. In analyzing the subsequent surveys, the basic rule adopted by Schultz was to count as highly annoyed the people who responded in the upper 27 to 29% of the annoyance rating scale if the steps were not named; and in the surveys using annoyance scales with all the steps named, so that the respondent could directly state his degree of annoyance, those people were counted as "highly annoyed" who said they were highly annoyed (even if, sometimes, this rating did not correspond to the top 29% of the scale).

Table A-1 shows the method for reckoning the percent highly annoyed in the different social surveys. The upper part of the table corresponds to those eleven surveys in which consistent counting was possible. These data cluster very well, as shown in Figure A-1. The lower part of the table concerns surveys in which the way the response data were reported for those people responding to the top 27% of the scale cannot be broken out at all; thus, these results cannot be directly compared to those of the other surveys.

The tabulated values corresponded either to a much greater part of the rating scale (40 to 50%) or a much smaller part (9%), leading to either significant overcounting or undercounting of those who were highly annoyed (in the same sense as those in the other surveys).

Table A-1: Method for Reckoning the Percent Highly Annoyed in Different Social Surveys

METHOD OF RECKONING PERCENTAGE HIGHLY ANNOYED IN VARIOUS SOCIAL SURVEYS. THE ENTRY "3/11", FOR EXAMPLE, MEANS THAT PEOPLE RESPONDING IN THE TOP THREE OUT OF ELEVEN CATEGORIES WERE COUNTED AS HIGHLY ANNOYED; THE DESIGNATION "SELF" MEANS THAT PEOPLE WERE COUNTED AS HIGHLY ANNOYED WHO SAID THEY WERE HIGHLY ANNOYED.

CLUSTERING SURVEYS	COUNTED AS HIGHLY ANNOYED	% UPPER END OF SCALE
SWEDISH AIRCRAFT	SELF	---
SWISS AIRCRAFT	3/11	27%
FRENCH AIRCRAFT	SELF	---
SECOND HEATHROW AIRCRAFT	2/7	29%
FIRST HEATHROW AIRCRAFT	2/7	29%
MUNICH AIRCRAFT	SELF	---
FRENCH RAILROAD	2/7	29%
PARIS STREET TRAFFIC	1/10	10%
SWISS ROAD TRAFFIC	3/11	27%
BBN 24-SITES STREET TRAFFIC	SELF	---
LONDON STREET TRAFFIC	2/7	29%
NON-CLUSTERING SURVEYS		
SWEDISH STREET TRAFFIC	1/11 (1968)	9%
SWEDISH STREET TRAFFIC	SELF (1975)	---
VIENNA STREET TRAFFIC	2/5	40%
FRENCH EXPRESSWAYS	2/4	50%
TRACOR LARGE CITIES	21/45	47%
TRACOR SMALL CITIES	21/45	47%
FIRST HEATHROW AIRCRAFT	3/7	43%

Plotting the results of these seven surveys leads to response curves that diverge considerably from the clustering group. Nevertheless, the average of the data from these nonclustering surveys lies close to the average of the clustering surveys. The not very surprising implication of this observation is that the average of a number of surveys, some of which overcount and some of which undercount the percentage of highly annoyed people, agrees with the average of surveys that do neither.

A.4.2 Translating Survey Noise Exposure Metrics to Day-Night Sound Level

Noise exposure in the different surveys had been evaluated in a number of noise impact metrics that were in vogue during the period (1961-1974) when these surveys were conducted. This included the Noise and Number Index (NNI) for aircraft noise; the 24-hour (or daytime) Equivalent Noise Level (including several variants developed in Germany); the French Isopsophic Index for aircraft noise; the 50-percentile noise level from a cumulative statistical distribution for road traffic; the CNR and the NEF for aircraft noise; and the DNL, itself.

Because the conductors of each of the surveys had some interest in comparing their findings with those of other surveys, many of them presented comparisons between the noise metric that they chose to use for their survey results and metrics used in other surveys. It was therefore possible for Schultz to set up regressions, valid only for the *community in question*, between a number of commonly used noise metrics. These comparisons yielded sufficient data to allow all the survey noise metrics to be transformed to the DNL in one, or at most two steps. Because the various noise metrics correlated highly with each other, the standard errors of estimate of these regressions were low, yielding fairly reliable translations of the noise exposure data to DNL's.

Whether the originally measured noise data in these surveys bore much relation to the exposure of the survey subjects is another question altogether, as discussed in Appendix B. This problem of the early surveys remains a problem today.

A.5 The Kryter/Schultz Dispute

In 1980, K. D. Kryter submitted a paper to the *Journal of the Acoustical Society of America* (Kryter, 1982a) in which he purported to show that the Schultz "Synthesis" significantly underestimates the annoyance associated with aircraft noise and over-estimates that due to surface traffic noise. "Because of the scientific and practical importance" of the "possibly misleading picture" presented by the Schultz paper, Kryter wished to establish an alternative analysis with the goal of correcting those errors. In fact, Kryter took two stabs at this alternative

analysis. In the first version of his paper (submitted to the *Acoustical Society of America* in May, 1980), he found a 10-dB difference in DNL for the same annoyance response between aircraft and road traffic noise, based on one set of arguments. When this paper was criticized by reviewers as arbitrary and incorrect in several particulars, Kryter rewrote the paper, shifting the ground of his argument but retaining the original conclusions.

In the version of his paper that Kryter finally submitted to the *Acoustical Society* in 1982, (Kryter, 1982b) he found the same differences between annoyance due to aircraft and road traffic noise, but for quite different reasons. In commenting on Kryter's paper, Schultz (1982a) states: "As for the differences that Kryter originally found between his and my interpretations of the results of previous social surveys on noise, they appear to have arisen from his original choice of aircraft noise surveys that were designed to exaggerate the annoyance response and his choice of street noise surveys that yielded low annoyance response, as well as from his errors in calculating the noise exposure. In his current version, he has exchanged one set of errors for another."

In addition, Kryter has been selective in the data points from the published aircraft noise surveys that he uses to establish his conclusions. Of the six data points published in the French survey, Kryter uses only four; of the twenty-seven data points from the Munich survey, he uses only four (and of these four, two of his values for "percent highly annoyed" disagree with the published values); of the seventeen points in the first Swedish survey, he uses only fourteen, and the same is true for the second Swedish survey.

Appendix B
Some Basics of Environmental Noise Exposure

Exposure, the product of level and duration, is the fundamental quantity of interest for assessing the environmental impacts of aircraft noise, since it is a convenient representation of the total acoustic energy produced by noise sources and potentially heard by people. Although much has been written about the nature of environmental noise exposure, the following summary should help the reader appreciate the relationships on which the models developed in this report are based.

B.1 The Outdoor Noise Environment

No environmental noises are heard in isolation. Even in sparsely populated areas a long term, time varying distribution of noise levels attributable to wind, water, rustling vegetation, animal sounds, and other natural causes can be measured and heard. Noises of human origin are superimposed upon the natural ambient noise distribution in highly predictable ways. In most areas inhabited by modern societies, noises of human origin are superimposed on each other as well. Galloway (1973) has shown that outdoor noise exposure grows directly with population density, as may be seen in Eq. B-1:

$$L_{dn} = 10 \log (\rho) + 22 \text{ dB} \qquad \text{(B-1)}$$

where: ρ is population density in people per square mile.

People make noise; the more people there are per unit area, the more noise is produced.

The mean DNL in uninhabited areas is generally 30-35 dB. In sparsely settled areas ρ less than or equal to 100) DNL values of 35-40 dB are common; for rural areas ρ about 500), the estimate is on the order of 50 dB; and in low density suburban areas ρ about 2,500), the estimate is about 55 dB. In industrial society transportation noise (individual vehicle passbys, traffic on

distant roads) is the major source of noise exposure. DNL values in the 60-70 dB range are common in major urban areas, and values as high as 80-85 dB are possible in the vicinity of major noise sources such as airports. The ever-present ambient noise distribution is a key concept for our purposes. It is therefore worthwhile to summarize what is known of its statistical structure.

Fidell, Horonjeff and Green (1981) have shown that the outdoor ambient noise environment of inhabited areas can be described statistically as the sum of two independent Gaussian distributions. One of these distributions, with a low mean and variance, is generated by noise sources distant from any given measurement point. The other distribution, with a higher mean and greater variance, is generated by noise sources in the immediate vicinity of any measurement point. The relative contributions of the local and distant noise-generating processes to the total noise exposure at any given location vary with population density, time of day, and frequency.

Some idea of the influence of human activity on the distant and local noise processes can be gained by examining some typical noise distributions. In remote areas of Canyonlands National Park in which the distant noise process dominates exposure throughout the day, ambient noise levels can fall as low as 20 dB(A), with a standard deviation as small as 1 dB. High flying aircraft, wind, water, and animal sounds can increase these levels for periods of a few minutes to levels on the order of 30 to 40 dB(A), with standard deviations of 5 to 10 dB. Figure B-1 plots long-term average ambient noise frequency of inhabited areas over a range of population densities.

At times of day when human activity is greatest in inhabited areas, the mean of the local process can exceed that of the distant process by 10 dB or more, thus dominating integrated metrics of noise exposure. At times of minimal activity (late night/early morning), the distant process predominates much of the time. There are also many times, however, when there is considerable momentary overlap between the distant and local processes. For example, if the mean of the distant process is 50 dB(A) and its standard deviation is 5 dB, and if the mean of the local process is 65 dB(A) and its standard deviation is 10 dB, then sounds on the order of 55-60 dB are fairly likely to occur both in the distant and local processes.

In areas of very high population density, the mean of the local process may not be much greater than that of the distant process, so that the total range of variability in exposure levels throughout the day is greatly reduced in comparison with the variability observed in areas of low population density. At all times of day and over all population densities, there is less variability in low frequency noise levels than in the high frequency levels. This is particularly true for the distant noise process, because long distance propagation of acoustic energy through the atmosphere favors low frequencies.

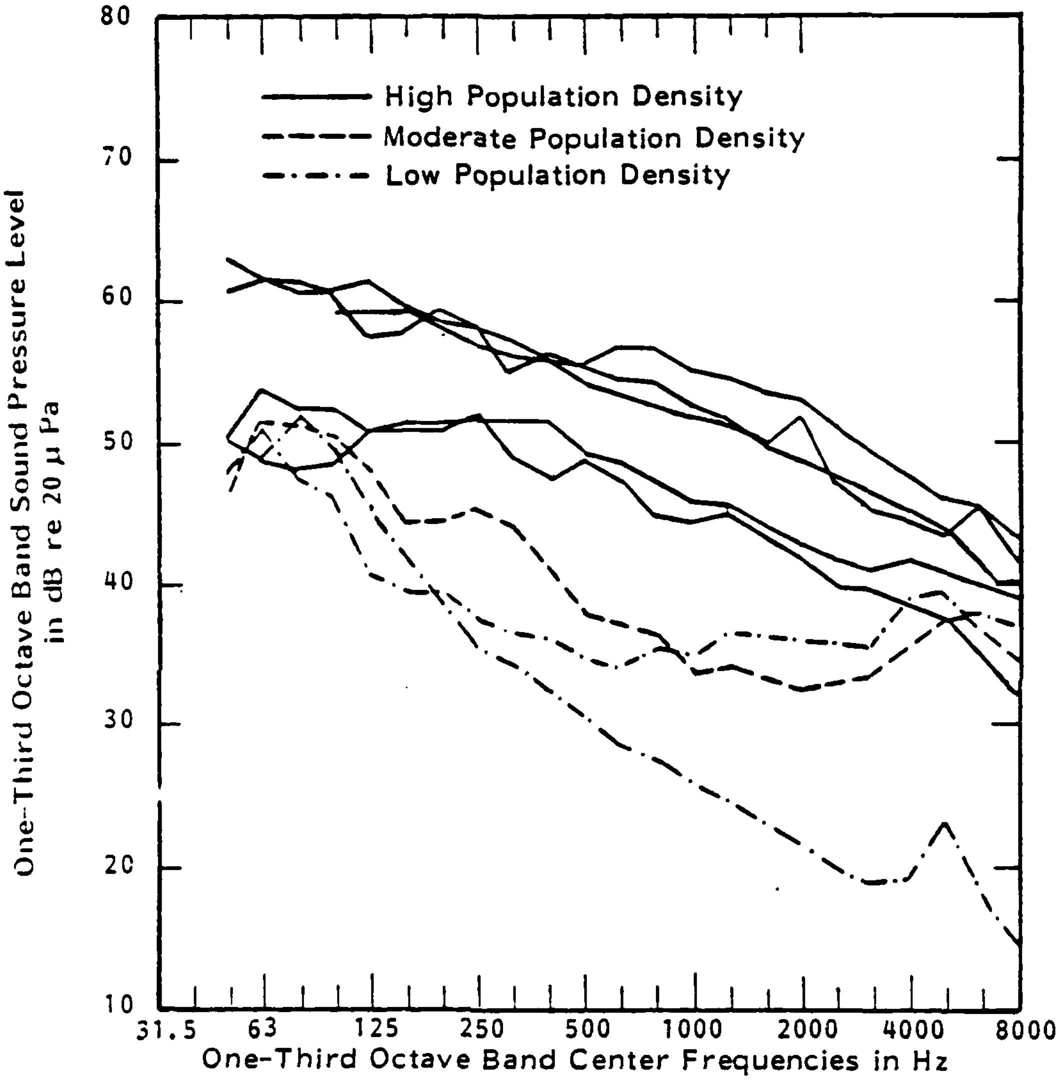

Figure B-1: Energy Mean Ambient Noise Frequency Measured in the 2 AM - 4 AM Period

B.2 The Indoor Noise Environment

B.2.1 Spatial Sampling of Individual Noise Exposure

Noise measurements are made by centrally locating an outdoor microphone with respect to the homes of respondents. It is assumed that neighborhood noise exposure so measured is representative of that of neighborhood residents. If one wishes to believe that such outdoor noise measurements are useful reflections of the exposure of individuals indoors, one must also assume either that most of the noise indoors, where the subjects spend most of their time, comes from outdoors, or that most of the annoying noise comes from outdoors. It is worthwhile to examine this assumption in detail.

B.2.2 Indoor *vs.* Outdoor Noise Exposure

Bishop (1973) has compared the statistics of simultaneous outdoor and indoor noise level measurements at a number of different locations. The results were expressed as hourly values for the centile levels L_1, L_{10}, L_{eq}, L_{50}, and L_{90}, for both the outdoor and indoor locations, together with the hourly variations of the outdoor-indoor difference in sound levels for each percentile (cf. Figures B-2 through B-4).

If the distribution of indoor noise levels were dominated by noises originating outdoors, one would expect that differences in levels of the indoor and outdoor distributions would remain nearly constant, even though the outdoor level might fluctuate widely. A constant difference could be attributed to the noise reduction afforded by the exterior walls of the building.

Instead, the figures show that this difference fluctuates widely over a range up to 30 dB. In fact, the fluctuation of the difference is typically far greater than that of either the outdoor or indoor level alone! Evidently, a large part of the noise in a house is generated indoors and is nearly independent of outdoor events. It is very doubtful, therefore, that an outdoor microphone can correctly characterize the noise exposure of subjects indoors.

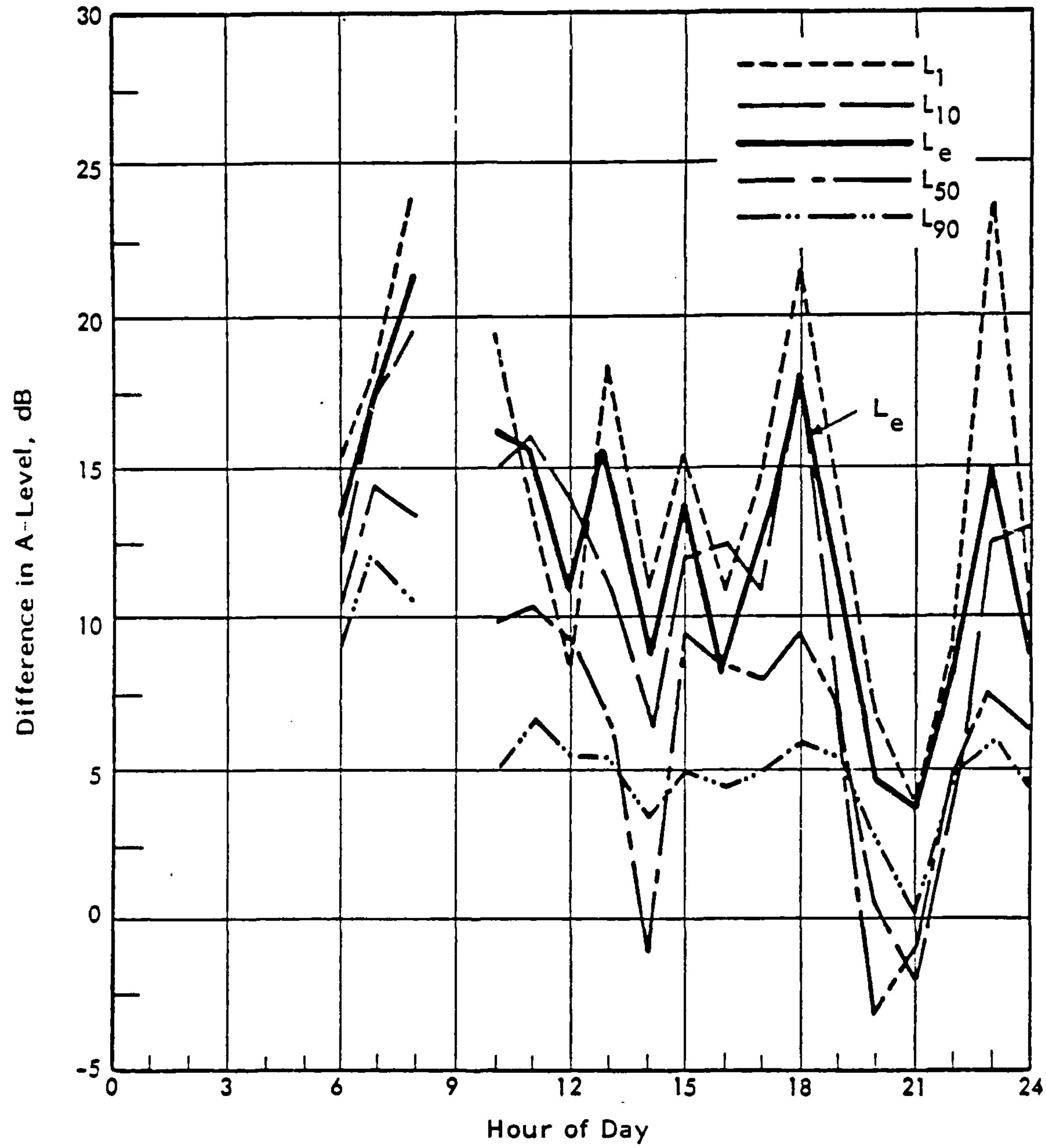

Figure B-2: Difference Between Outside and Inside Hourly Noise Levels at a Suburban Residential Site

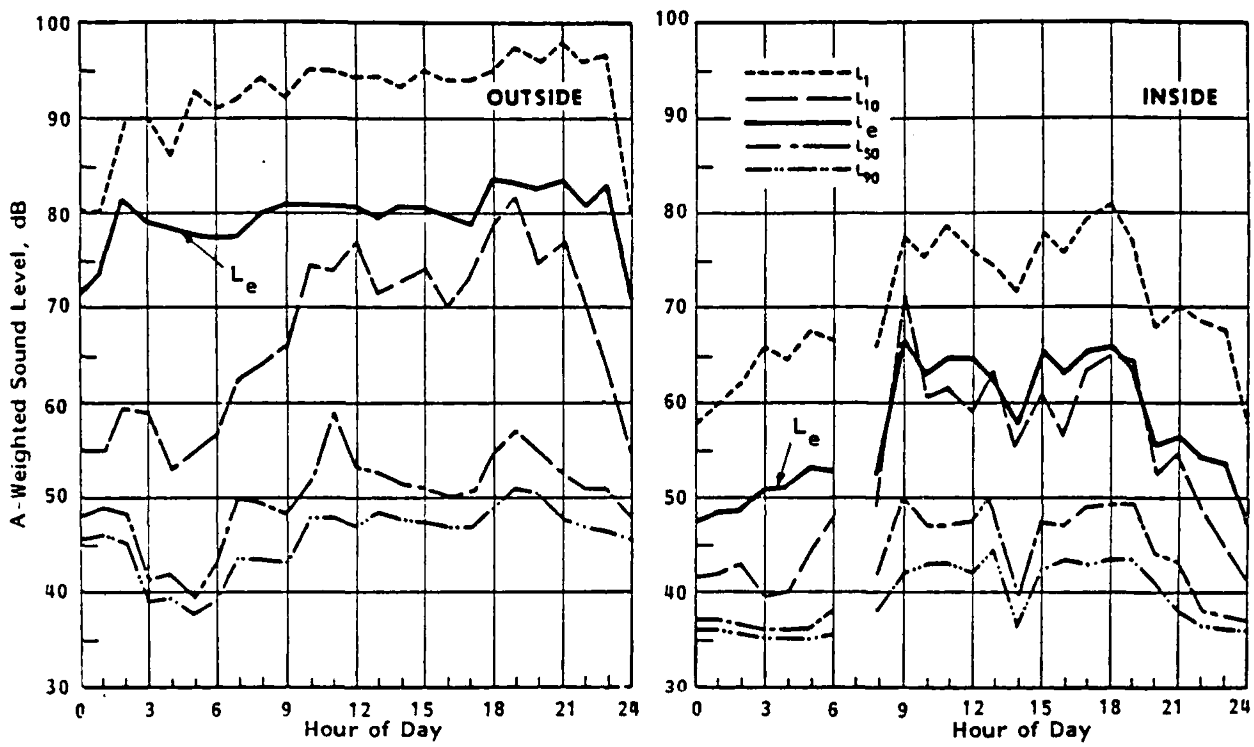

Figure B-3: Hourly Noise Level Time Pattern Outside and Inside a Residential Site Under Landing Path at LAX

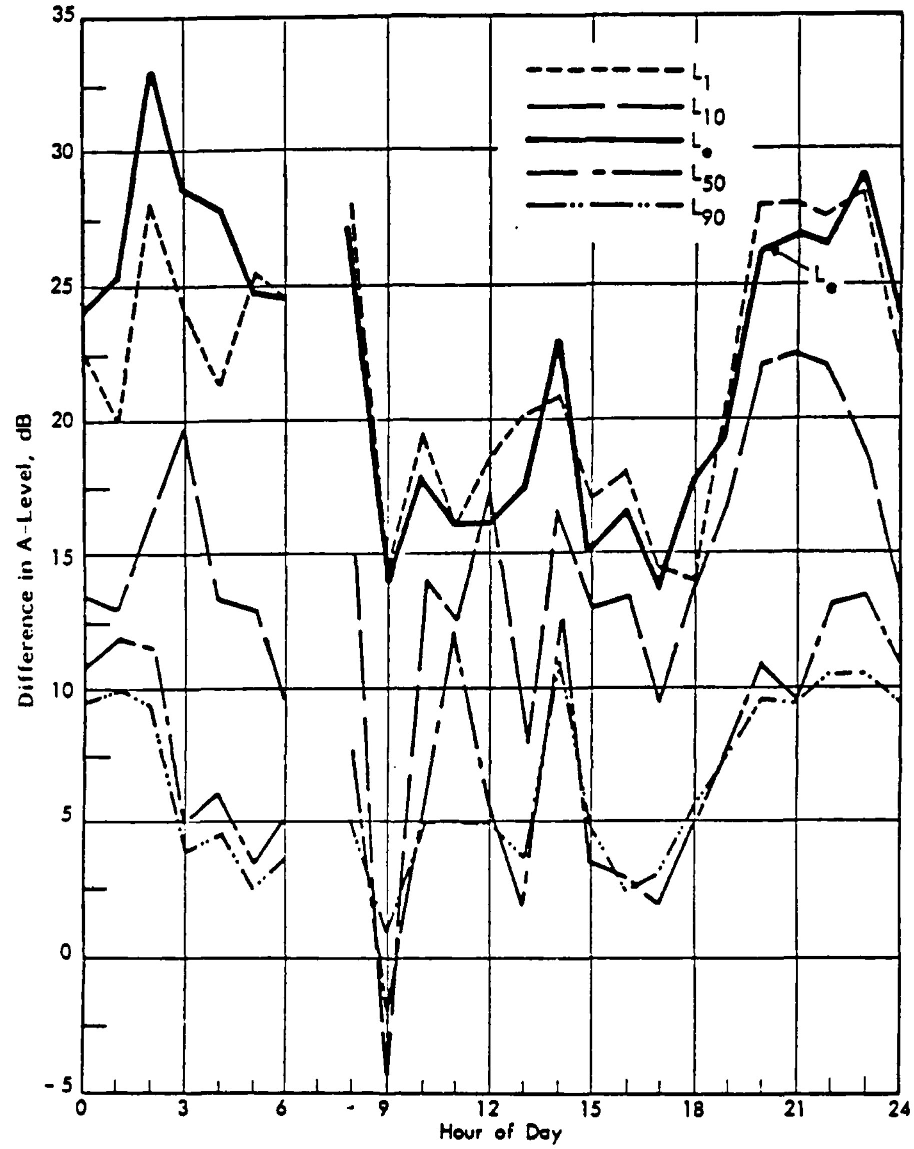

Figure B-4: Difference Between Outside and Inside Hourly Noise Levels at a Residential Site Under Paths at LAX

B.2.3 Place Versus Personal Exposure Differences

This is not the end of the problem, however. It cannot be assumed that a microphone placed inside the house yields a better characterization of the occupants' noise exposure than an outdoor microphone. The results of a pilot study that compared noise exposure recorded by a fixed indoor microphone with the exposure recorded by a microphone mounted near the ear of a mobile occupant are illuminating.

The fixed microphone was placed in the middle of the living room, on the second floor of a three-floor house. The moving microphone was attached to the shoulder of the occupant, and transmitted its signal to a radio receiver in the living room. The signals from both microphones were recorded simultaneously on a two-channel tape recorder for two periods of about 45 minutes. During the first recording period, the activities of the occupant ranged over all three floors of the house and included typing, handwashing, clearing the table, pouring a drink, rinsing glasses, making beds and various other ordinary household chores. The second period included vacuum cleaning of the carpet in the living room.

A comparison of the levels recorded by the fixed and mobile microphones is shown in Figure B-5 for the first 45 minute sample and Figure B-6 for the second. The cumulative distribution from the fixed microphone bears almost no relation to that from the moving microphone. In the first period, the L_{10} levels from the two microphones differed by about 17 dB, while the L_5 levels differed by 21 dB. Only for centile levels of 50 or more (i.e., the background noise levels) do the two distributions approach agreement.

During the second recording period, the predominant noise of the vacuum cleaner (in the same room with the fixed microphone) reduced the difference between the noise exposures recorded by the fixed and moving microphones, but a substantial difference remained.

The data shown in Figures B-5 and B-6 demonstrate that a fixed microphone, no matter where it is placed, gives a poor account of the actual noise exposure of active occupants of a dwelling.

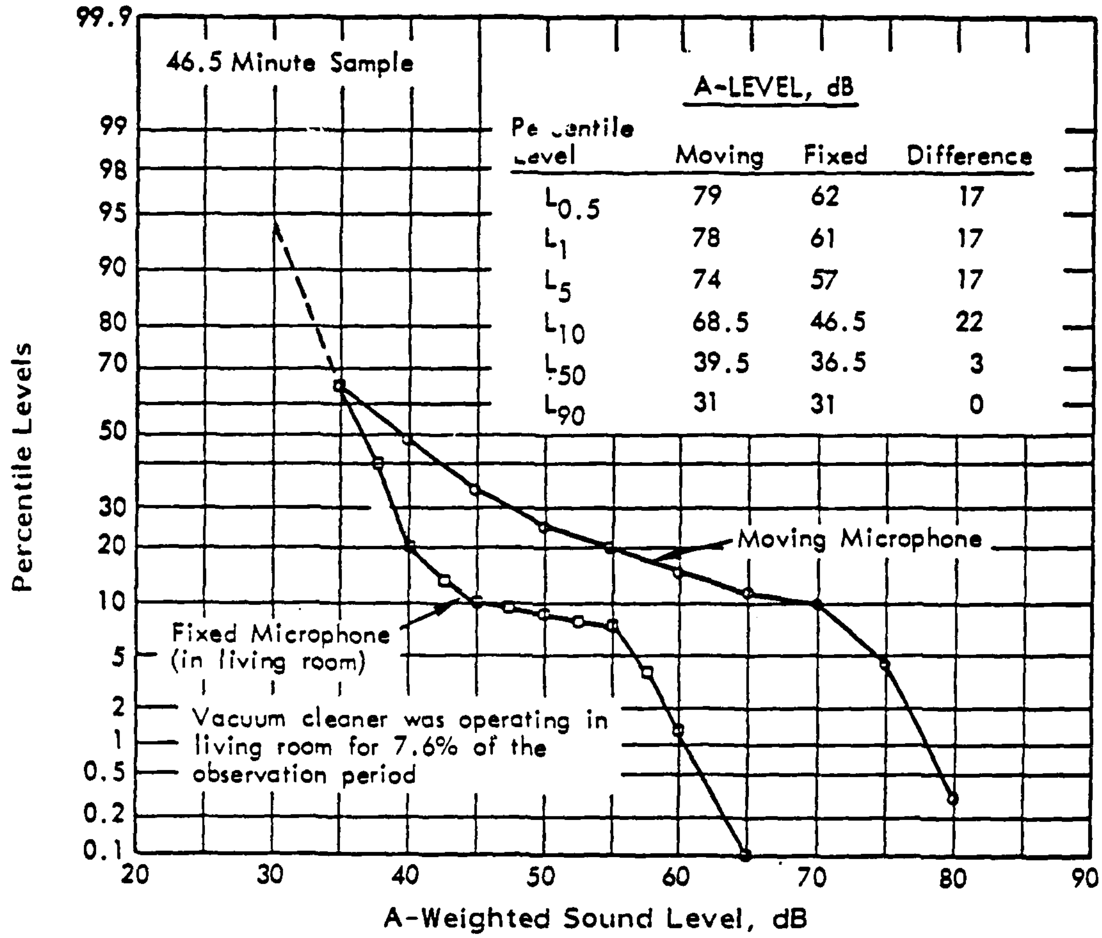

Figure B-5: Comparison of Cumulative Distribution of Levels for Fixed *vs.* Moving Index Microphones Without Vacuum Cleaner Noise

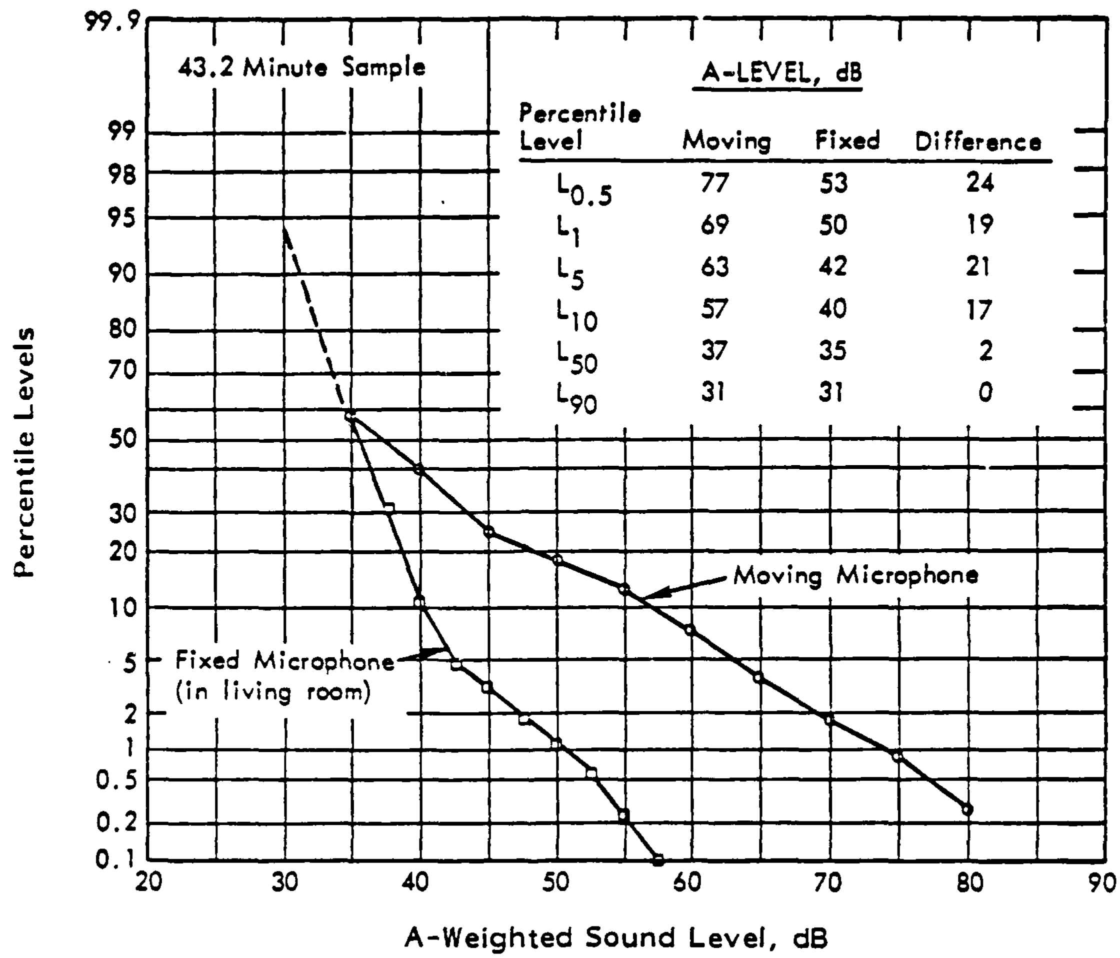

Figure B-6: Comparison of Cumulative Distribution of Levels for Fixed and Moving Indoor Microphones, with Vacuum Cleaner in Room

B.3 The Relevance of Outdoor Background Noise to Indoor Exposure

Findings of this sort raise serious questions about the relevance of outdoor background noise as it affects the responses of people indoors, because much of the time they simply do not notice it. These questions throw doubt on once-popular noise ratings such as the Traffic Noise Index (TNI) and the Noise Pollution Level (NPL), which make a great point of accounting for the variability (i.e., the level fluctuations) of the outdoor noise exposure. The major part of the noise variability that people actually hear is probably self-generated. Thus the range (L_{10} - L_{90}) of outdoor noise levels may be largely irrelevant for purposes of predicting the annoyance responses of indoor populations.

Indeed, it is questionable whether centile of outdoor noise distributions can be relied on at all to predict annoyance. The reason is that they are too anonymous! Even an L_1 doesn't necessarily reflect any identifiable event that is likely to catch the attention of an occupant in the midst of an activity. An L_{10} refers only to the noise level that a truck may have made at some distance down the road, not to anything remarkable about its passage.

In short, the relationship between outdoor noise levels and individual noise exposure is not straightforward. The ecologic fallacy as applied to noise exposure is that outdoor noise exposure measurements in residential neighborhoods represent individual noise exposure. People are not stationary objects; they may spend considerable time away from home in much quieter or noisier noise environments; their homes attenuate outdoor noise levels by 10 to 20 dB (or more); and the levels of indoor noise environments are often higher than outdoor noise environments due to the operation of household appliances and other discretionary noise sources. As a general rule, however, it is common for long-term outdoor noise measurements to overestimate indoor residential noise levels, especially in noisier neighborhoods.

An important exception to this rule of thumb is low frequency noise. For example, a sonic boom heard indoors is often more annoying than one heard outdoors, because residential and other structures transduce low frequency inaudible energy into highly audible secondary emissions, especially rattling noises.

For all these reasons, there is no simple transform that can be used to estimate individual exposure from either indoor or outdoor noise exposure. Since it is impractical to directly measure individual noise exposure on a large scale, it is doubtful that individual exposure will ever be translated into useful data. An alternative concept (that of a noise dose) is developed in Chapter 2 to account for this source of uncertainty.

B.4 The Nature of Aircraft Noise Exposure

Aircraft noise emissions can be characterized in a variety of ways. The measures which produce the highest numeric values are the instantaneous peak level (the greatest sound pressure level attained at any time during a flyover, even if the duration of the peak is only a small fraction of a second), and the single event sound exposure level. The latter measure is the sum of all the sound energy occurring during the course of a noise event of arbitrary duration, normalized to a hypothetical 1-s interval. This normalization is accomplished by trading duration for energy, so that a factor of 10 (e.g., the ratio of 10 seconds to 1 second) is expressed as an additional 10 dB of integrated level. Thus, the sound exposure level of an aircraft flyover longer than 1 s is higher numerically than the actual peak level of the flyover.

Calculating sound exposure levels for single events is a convenient way to compare the total noise energy of flyovers of different durations. It also simplifies estimating longer term exposure by permitting simple logarithmic manipulations of the noise energy in multiple flyovers to calculate 24-hour equivalent levels, or even annual average DNL values.

According to some estimates, approximately a million people in the United States are exposed to aircraft produced DNL values in excess of 80 dB. These are mostly people living close to major airports, who experience both large numbers of flyovers (hundreds or more per day) and high sound exposure levels for individual flyovers. A great many more people, however, live in neighborhoods with exposure levels in the range of DNL = 70 dB or more. These are people who do not live directly beneath approach or departure flight paths, but who live within a few thousand meters of flight tracks. Their numbers are probably comparable to those who suffer similar exposure levels because they live close to major highways.

The point of these comparisons is to emphasize that high exposure levels are not generally produced by very high individual event levels, alone, but rather by a combination of moderate individual event levels and large numbers of events. In the aggregate, the "aircraft noise problem" in residential areas is more a problem of multiple exposures to moderately high level noise events (say, on the order of 70-80 dB as heard indoors) than a problem of small numbers of exposures to very high level (say, in excess of 85 dB indoors) individual events.

Appendix C
Decision Making Under Conditions of Uncertainty and Risk

This Appendix introduces concepts underlying human perceptual decision making to aid readers unfamiliar with them in understanding Chapter 4. Readers interested in a fuller treatment of the topic are referred to Raiffa and Schlaifer (1961) and to Swets (1964).

C.1 Bayesian Inference

It should be noted first that most real world decision making is based on incomplete or uncertain information, and that meaningful decisions generally entail real costs and payoffs for decision outcomes. For example, one rarely has complete and reliable information on which to base a decision to vote for one political candidate or another; or to buy one used car or another; or to make one financial investment or another. Uncertainty is the rule rather than the exception in the decision making of everyday life. Furthermore, the outcomes of one's real-life decisions have real and sometimes substantial costs and payoffs. A correct decision about an investment, for example, can be financially rewarding, while an incorrect decision can cost dearly.

Even complicated decisions can be broken down into series of binary (yes-no) decisions. It is convenient to concentrate on this form of elementary decision making because it simplifies the discussion of correct and incorrect decisions and their costs and payoffs. Consider a situation in which one has essentially no useful information on which to base a decision: a fair (unbiased) coin toss. The coin can land as either heads or tails, and one can decide to predict either outcome independently of which way it actually lands. A decision in this context is tantamount to a guess, however, since there is no information on which to base a rational decision.

Table C-1 shows all possible combinations of decision outcomes in this situation. Note that there are two forms of correct decision and two forms of incorrect decision. If the payoffs for both types of correct decisions are equal, there is no rational basis for deciding to guess heads any more often than tails.

Suppose, however, that the payoff for a correct decision when the coin lands as heads is substantially greater than the payoff for a correct decision when the coin lands as tails. For example, suppose that the payoff for a correct decision with respect to a head is a quarter, while the payoff for a correct decision with respect to a tail is only a nickel. Suppose further that the costs for both types of incorrect decisions are equal.

Table C-1: Decision Outcomes for Coin Tosses

YOUR DECISION	HEAD	TAIL
Head	Correct	Incorrect
Tail	Incorrect	Correct

Even though one has no more information than before about how the coin will land, there is now an excellent reason to consistently guess heads rather than tails: the payoff is five times greater. The reader can easily appreciate how alternate ratios of costs to payoffs should influence decisions in cases in which there is no real information on which to base a decision.

Suppose, however, that the decision maker does have some useful, if imperfect, information based on a series of observations. After a great many tosses, assume that it becomes apparent that the coin being tossed is not a fair coin, but rather one that has a heads. For example, suppose that it is known that the coin lands as heads three quarters of the time. Shouldn't the decision maker take these *a priori* odds (the odds in favor of heads prior to any particular toss) into consideration, along with the costs and payoffs of the various decision outcomes?

And what if the decision maker has yet another source of partial information about each individual coin toss? Suppose, for example, that a relationship is observed between the height of the coin toss and the way it lands, so that the probability of landing as heads is greater the higher the toss? If the decision maker could estimate how high the coin was tossed while it was still in the air, should not this information be combined in some way with the *a priori* odds of landing heads and with the costs and payoffs before a decision is made?

In fact, the best rule for combining all these sources of information while also taking into consideration the costs and payoffs of the decision outcomes has been well known for many years. The rule is known as Bayes' law, after the English clergyman who formulated the law of inverse probabilities a century and a half ago. In this context, Bayes' law holds that the *a posteriori* odds in favor of an hypothesis (e.g., that a coin will land one way or the other) are equal to the product of the *a priori* odds (the odds known in advance, before the coin toss, as the result of long observation) and the likelihood ratio of the observation.

In this example, information about the likelihood ratio is given by the height of the coin toss, since it was assumed above that the higher the coin is tossed, the more likely it is to land as heads. Thus, if the coin is tossed one foot in the air, the odds in favor of landing as heads might be 2:1; if tossed two feet in the air, the odds might be 4:1; etc.

C.2 Application to Human Signal Detection

Considerable success has been achieved in modeling human perceptual decision making as a Bayesian process (cf. Swets, 1964). In fact, a well-developed Theory of Signal Detectability has become the standard paradigm for understanding and predicting the detectability of visual, auditory, and other sensory information by human observers (Green and Swets, 1966). Perhaps the most fundamental distinction made in this view of perceptual decision making is the difference between sensitivity and response bias.

"Sensitivity" refers to the decision maker's true sensory capability to distinguish signals from the background noise. "Response bias" refers to the influence of the costs and payoffs on the decision maker's willingness to report the presence or absence of a signal independently of any sensory information.

This distinction can be classified in a particular decision-making task. Imagine that an airport neighborhood resident engaged in routine household living is asked once per minute to report whether an aircraft flyover was heard in the preceding minute. The resident's task is thus to distinguish between the noise of an aircraft flyover and the noise of all other local noise sources, such as street traffic, vacuum cleaners, TV, etc. The resident's yes ("I heard a flyover during the last minute") and no ("I didn't hear a flyover during the last minute") responses are categorized in Table C-2.

Table C-2 differs from Table C-1 only in the respect that the two correct and the two incorrect decisions are given new names. A decision to report the occurrence of a flyover when a flyover occurred during the preceding minute is now termed a "hit", while a decision to report the presence of a flyover when one did not occur is termed a "false alarm".

It has long been known that the costs and payoffs associated with hits and false alarms have a dramatic influence on the willingness of people to report the presence or absence of signals. For example, if the resident is paid a $10.00 bonus for each hit and fined nothing for a false alarm, the percentage of yes responses can be expected to approach 100%. Conversely, if the resident is fined $10.00 for each false alarm and paid nothing for a hit, the percentage of yes responses can be expected to approach 0%. If the decision maker is paid and fined equal amounts for hits and false alarms, the percentage of yes responses can be expected to lie at an intermediate value.

Figure C-1 plots the probabilities of hits and false alarms against each other in a form known as a Receiver Operating Characteristic (ROC) curve. On such a plot, the performance of a decision maker who has absolutely no physical information about the presence or absence of a signal lies along the positive diagonal. This is also known as the "line of chance performance",

Table C-2: Decision Outcomes for Aircraft Detection Example

	ACTUAL STATE OF AFFAIRS	
Resident's Decision	Aircraft Present	Aircraft Absent
YES (Aircraft Present)	Hit	False Alarm
NO (Aircraft Absent)	Miss	Correct Rejection

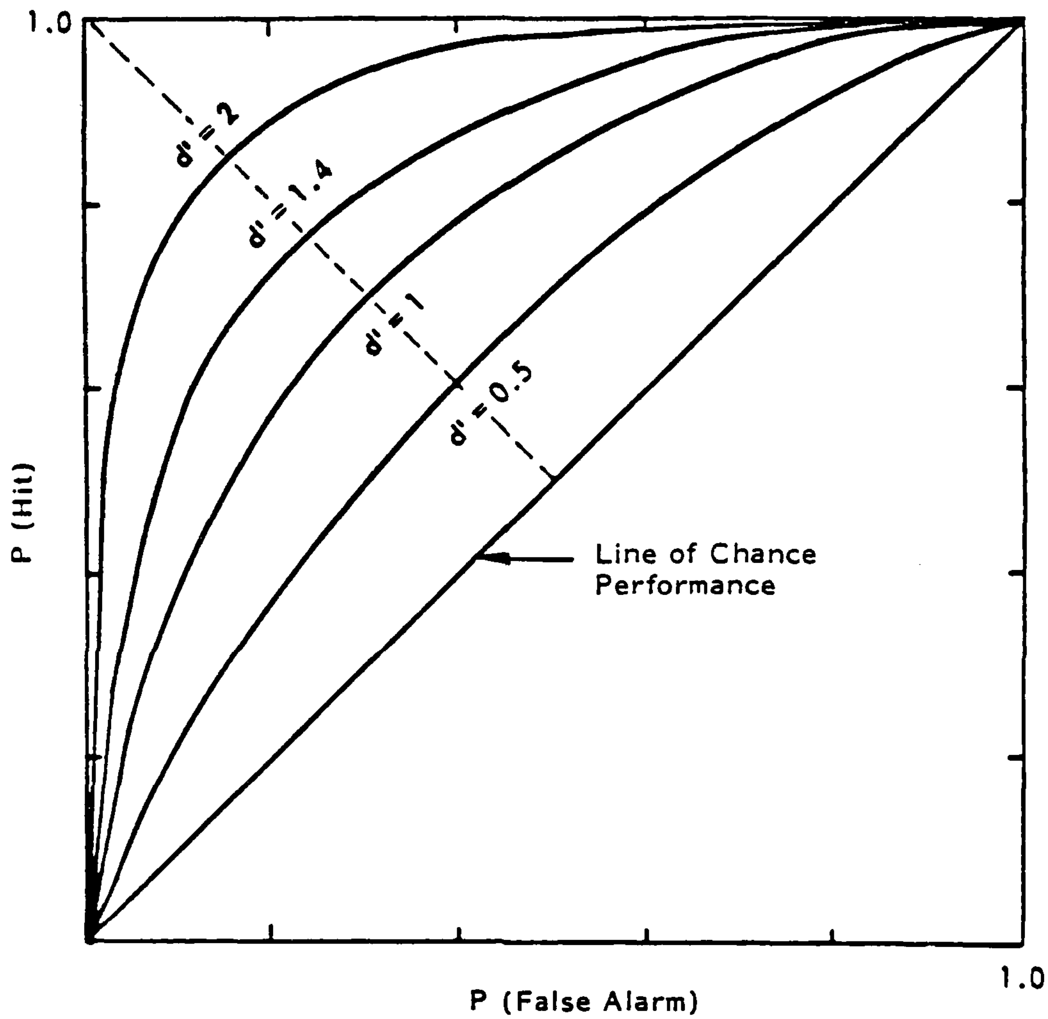

Figure C-1: A Family of ROCs for Equal Variance, Gaussian Distributions of Noise and Signal Plus Noise

since for each increment in the probability of a hit there is an equal increment in the probability of a false alarm.

The three points marked on the ROC curve correspond to ratios of hits to false alarms associated with the three sets of costs and payoffs for hits and false alarms described in the previous paragraph. Note that even though the resident's true sensitivity to distinguish aircraft flyovers from other neighborhood noises is fixed, the ratios of hits to false alarms vary directly with the costs and payoffs of the decision outcomes.

The ROC curve for the resident's responses is in fact an iso-sensitivity curve. The superficial differences in the resident's ability to detect aircraft flyovers (produce hits) are simply the product of his willingness to respond yes or no, not his true ability to hear aircraft flyovers.

A well-accepted explanation for the curvilinear shape of the human ROC curve is that it reflects the shapes of the probability distributions of the background noise and the signal plus noise conditions, as illustrated in Figure C-2. The decision to say yes or no is made with respect to a value of the likelihood ratio (the ratio of the probabilities that an observation arose from each of the two distributions in Figure C-2). The criterion value for the likelihood ratio is established by the decision strategy (e.g., minimizing costs associated with incorrect decisions, maximizing payoffs associated with correct decisions, maximizing the expected value of all decisions, etc.), which in turn is based on the actual costs and payoffs of decision outcomes and the *a priori* odds.

As the criterion value of the likelihood ratio shifts to reflect different decision strategies, the ratio of hits to false alarms changes correspondingly, even though the two underlying probability distributions remain fixed. The probability of a hit associated with any criterion value is simply the area to the right of the criterion that lies underneath the envelope of the rightmost distribution in Figure C-2. The probability of a false alarm is likewise the area to the right of the criterion that lies underneath the envelope of the leftmost distribution in Figure C-2. As the value of the likelihood ratio criterion increases (moves from left to right in Figure C-2), a decision maker's operating point on his ROC curve moves from the lower left corner to the upper right corner of Figure C-1.

The difference between the means of the two distributions of Figure C-2 , normalized by division by the standard deviation of the distribution of noise alone, is a statistic known as d'. This statistic is a scalar quantity whose value is completely independent of any value chosen for a likelihood ratio criterion for decision making. For a noise distribution of fixed variance, d' simply increases linearly with signal-to-noise ratio: the greater the signal) to-noise ratio, the more detectable a signal becomes. In terms of the ROC analysis illustrated in Figure C-2, d' represents the distance along the negative diagonal from the line of chance performance to a point on the ROC curve.

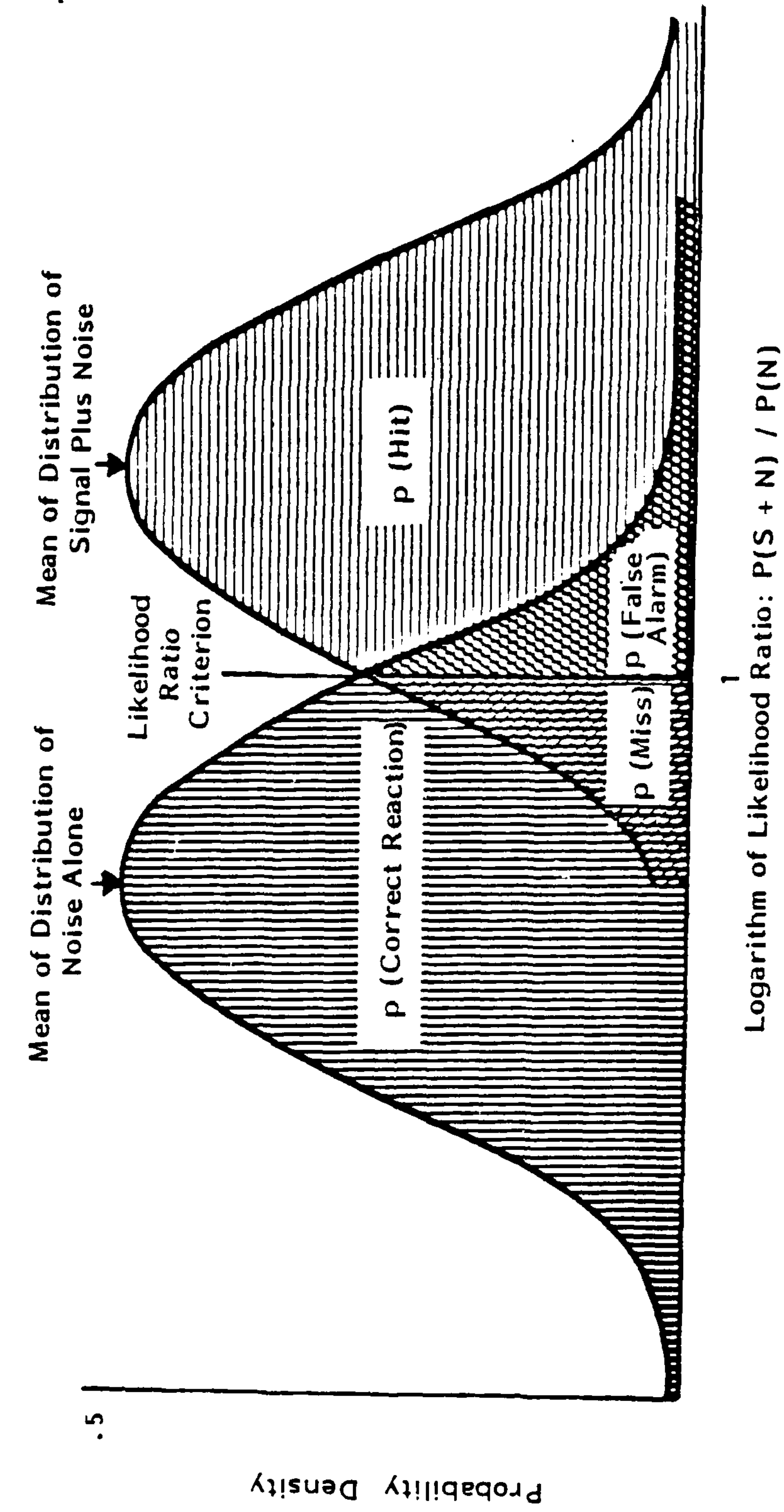

Figure C-2: Distribution of Probability of Occurrence of Noise Alone and Signal Plus Noise Conditions

C.3 Summation

Any report of a decision about the presence or absence of a condition confounds the influences of two sets of factors: 1) the decision maker's true ability to discriminate the condition's presence from its absence ("sensitivity"); and 2) the decision maker's willingness to assert the presence or absence of the condition independently of any physical information ("response bias"). The perceptual decision making of people can be modeled as the result of a rational process, in which people adjust their criterion for reporting the presence or absence of a condition in accordance with well defined influences of both sets of factors.

Appendix D
On the Roles of Costs and Payoffs and *A Priori* Odds in the Model of Annoyance

The model described in Chapter 4 assigns only minor roles in annoyance decision making to two of the factors which play major roles in standard Bayesian inference: the *a priori* odds of that a signal will occur and the costs and payoffs of decision outcomes. This appendix develops the mathematical arguments which support this position.

Consider the following simple detection problem. The background noise has a Gaussian distribution with mean zero and unit variance. The signal distribution has the same variance but a mean greater than that of the noise alone. Suppose the detector's strategy is to maximize the expected value of the decisions.

The likelihood ratio, L(x), is well known to be the optimal basis for a decision criterion. The value of likelihood ratio of a particular observation, x, is given by

```
L(x)  =  f(x|s)/f(x|n)  =  [exp-(x)d')**2/2]/[exp-x**2/2]
                                      or
ln L(x)  =  xd'  - d'**2/2                                  (D1)
```

As described by Green and Swets (1966, p. 22), if the strategy is to maximize the expected value of decisions, one should select a value of likelihood as a decision criterion; call it L(*), so that

$$L(*)=[P(n)/P(s)] * [(V_{00} + C_{01})/(V_{11} + C_{10})] \qquad (D2)$$

where P(s) is the *a priori* probability of the signal, P(n)=1 - P(s), the *a priori* probability of noise alone. The terms V_{ij} or C_{ij} are the values and costs associated with the two possible signals and two possible responses (See Table C-1).

Suppose that either the *a priori* probability of a signal is altered, or the values and costs are

changed so that L(*) is modified. How will such changes affect the value of decision criteria as measured on x? To derive this relation, we need to determine the value of x associated with a particular likelihood criterion, L(*). Solving Eq. D1 for x, we have

$$x(*) = \ln L(*)/d' + d'/2 \qquad \text{(D3)}$$

Thus, if the values and costs are equal and, if both signal and nonsignal are equally likely, then L(*) = 1, see Eq. D2. In which case, Eq. D3 indicates that the optimum criterion along x, x(1), is simply d'/2, see Eq. D3. If the values and costs are altered, the value of L(*) is changed, which, in turn, will change the optimum criterion on x. It is convenient to measure the relative change in x from the L(*)=1 condition,

$$x(*)/x(1) = [\ln L(*)/d' + d'/2\ ] \ /\ [\ d'/\ 2] \qquad \text{(D4)}$$

$$= 2 * \ln L(*)/(d'**2) + 1$$

As can be seen by this equation, the relative change in criterion along x varies inversely with d'**2, so that, unless d' is small, the relative change is slight. Assuming that relative changes in x are proportional to signal power, which is approximately true for the human observer detecting a change in noise level, then the changes in x measured in terms of decibels are simply

$$10 \log [\ 2*\ln L(*)/d'**2 + 1\ ] \quad \text{if } x(*)/x(1) > 1 \text{ or}$$

$$10 \log [-2*\ln L(*)/d'**2 + 1\ ] \quad \text{if } x(*)/x(1) < 1. \qquad \text{(D5)}$$

Table D-1 displays calculations for d' = 1 (a typical detection value) and d' = 1,000 (a typical annoyance value) when the optimum likelihood ratio changes by several orders of magnitude.

Changing the optimum criterion by varying the values and costs or the *a priori* probability of a signal changes the criterion along x by about 23 dB for the detection case (d' = 1) and less

Table D-1: Effects of Extreme Signal-to-Noise Ratios on Likelihood Ratio Criterion

OPTIMUM LIKELIHOOD VALUE	x (if d' = 1)	x (if d' = 1000)
0.001	-6.4	500
0.01	-4.1	500
0.1	-1.8	500
1	0.5	500
10	2.8	500
100	5.1	500
1000	7.4	500

than 0.001 dB for the larger d' (annoyance value). For the annoyance case, therefore, the change is negligible.

It follows that the influences of the *a priori* odds and the costs and payoffs diminish greatly with signal-to-noise ratio. Decisions about the detectability or the annoyance of signals of low d' (those which are close in level to the mean of the distribution of levels of background noise) are influenced much more by the *a priori* odds of signal occurrence and the costs and payoffs of decision outcomes than decisions about the annoyance of of high d' signals (those with much higher levels than the mean of the distribution of background noise levels).

Appendix E
Spreadsheet Calculations for Intrusive Noise Model

Table E-1: Worksheet to Calculate Annoyance for People in an Unfavorable State, Who are Focused on the Disturbance

WORKSHEET TO CALCULATE ANNOYANCE OF INDIVIDUAL NOISE INTRUSIONS UNDER THE FOLLOWING CONDITIONS DURATION: 10 SECONDS

AFFECTIVE STATE: -5 (UNFAVORABLE) RESULTING TOLERANCE INDEX: -10 RESULTING 10 LOG (DECISION CRITERION): -10

CONCENTRATION ON -5 (FOCUSED ON DISTURBANCE) DURING ACTIVITY

SEL OF INTRUDING NOISE IN DB(A)

	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
10 LOG d'	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
NOT AT ALL ANNOYED	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...
MODERATELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES
VERY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
10 LOG d'	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
NOT AT ALL ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MODERATELY ANNOYED	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
VERY ANNOYED	...	...	...	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table E-2: Worksheet to Calculate Annoyance for People in a Neutral State, Who are Focused on Tasks

WORKSHEET TO CALCULATE ANNOYANCE OF INDIVIDUAL NOISE INTRUSIONS UNDER THE FOLLOWING CONDITIONS DURATION: 10 SECONDS

AFFECTIVE STATE: 0 (NEITHER FAVORABLE NOR UNFAVORABLE) RESULTING TOLERANCE INDEX: 5 RESULTING 10 LOG (DECISION CRITERION): 5

CONCENTRATION ON ONGOING ACTIVITY: 5 (FOCUSED ON TASKS)

SPL OF INTRUDING NOISE IN DB(A)

	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65
10 LOG (D')	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
NOT AT ALL ANNOYED	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...		...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...
MODERATELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES
VERY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
10 LOG (D')	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
NOT AT ALL ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MODERATELY ANNOYED	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
VERY ANNOYED	...	...	...	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table E-3: Worksheet to Calculate Annoyance for People in an Unfavorable State, Who are Neither Focused on the Disturbance nor on Tasks

WORKSHEET TO CALCULATE ANNOYANCE OF INDIVIDUAL NOISE INTRUSIONS UNDER THE FOLLOWING CONDITIONS   DURATION: 10 SECONDS

AFFECTIVE STATE: 5 (UNFAVORABLE)   RESULTING TOLERANCE (NOFT): -5   RESULTING 10 LOG (DECISION CRITERION): -5

CONCENTRATION ON ONGOING ACTIVITY: 0 (NEITHER FOCUSED ON TASKS NOR FOCUSED ON DISTURBANCE)

SPL OF INTRUDING NOISE IN DB(A)

	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
[illegible]	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
NOT AT ALL ANNOYED	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...
MODERATELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES
VERY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
[illegible]	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
NOT AT ALL ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MODERATELY ANNOYED	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
VERY ANNOYED	...	...	...	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table E-4: Worksheet to Calculate Annoyance for People in a Favorable State, Who are Focused on Tasks

WORKSHEET TO CALCULATE ANNOYANCE OF INDIVIDUAL NOISE INTRUSIONS UNDER THE FOLLOWING CONDITIONS DURATION: 10 SECONDS

AFFECTIVE STATE: 5 (FAVORABLE)

RESULTING TOLERANCE INDEX: 10

RESULTING 10 LOG (DECISION CRITERION): 10

CONCENTRATION ON: 5 (FOCUSED ON TASKS) ONGOING ACTIVITY

SPL OF INTRUDING NOISE IN DB(A)

	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65
10 LOG (d'(t))	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
NOT AT ALL ANNOYED	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	...
MODERATELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	YES
VERY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
10 LOG (d'(t))	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
NOT AT ALL ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
SLIGHTLY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MODERATELY ANNOYED	YES	YES	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...	...	...	...	...	...	...
VERY ANNOYED	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YES	YES	...	...	...	...	...	...
EXTREMELY ANNOYED	...	...	...	...	...	...	...	...	...	...	...	...	...	...	YES	YES	YES	YES	YE	YES

Glossary

Ambient noise distribution: A distribution of sound pressure levels observed for some duration at some location (see Appendix B for greater detail).

A-weighting network: A frequency-equalizing function intended to approximate the sensitivity of human hearing to moderate level sounds.

Category measurement scale: An absolute judgment scale in which mutually exclusive labels are used to describe subjective intensity.

d': An index of the detectability of a signal based on the normalized difference between the means of the distributions of noise alone and signal plus noise.

Decision epoch: The period of time during which an annoyance decision is made.

Day-Night Average Sound Level: A 24-hour energy average sound level with a 10 dB adjustment for night (10 PM - 7 AM) time.

Distant noise process: One component of an ambient noise distribution with a relatively low mean and variance attributable to noise sources distant from any given measurement point.

Equivalent level: The energy average of a signal over a specified duration.

False Alarm: The outcome of a decision to report a signal's presence when one is not present.

Hit: The outcome of a decision to report a signal's presence when one is present.

Insertion loss (of a residential structure): A frequency-specific reduction in signal energy of an outdoor sound propagating through the walls of a building; in general, low frequency energy is attenuated much less than high frequency energy. Reductions in signal energy of approximately 15-25 dB(A) are common, varying with window openings.

DNL: (see Day-Night Average Sound Level)

Likelihood Ratio: The probability an observation will occur given that it is generated by a signal process (i.e., a distribution of signal plus noise), divided by the probability an observation will occur, given that it is generated by a noise (i.e., a distribution of noise alone).

Noticeability: An acoustic signal's level relative to the ambient noise distribution in a

given environment at which an individual, engaged in an activity other than expressly listening for sounds, becomes aware of its presence.

Perceived noise level: A measure of apparent noise calculated from full or one-third octave band sound pressure levels.

Response bias: The willingness to report the presence or absence of a condition independently of any available physical information.

Signal to Noise Ratio: The relative level (in dB) of some characteristic of a signal (e.g., its rms value) and the corresponding characteristic of a noise distribution.

Variance: The sum of the squares of the deviations from the mean sound pressure level in a distribution of measured sound pressure levels.